Light fragment production in the interaction of 84 MeV/nucleon ^{12}C with ^{208}Pb

B. Grabež
Institute of Physics, 11001 Belgrade, Yugoslavia

R. Beckmann,* P. Vater, and R. Brandt
Kernchemie, Philipps-Universität, D-3550 Marburg, Federal Republic of Germany
(Received 2 December 1985)

Using a CR-39 plastic track detector, it is proved that the low energy light fragments ($5 \leq Z \leq 26$) produced in the interaction of 84 MeV/nucleon ^{12}C with a Pb target originate predominantly from the binary breakup. The characteristics of light fragments and their corresponding heavy partners have been determined. The dependence of measured parameters on the atomic numbers of light fragments is observed. The obtained values of the velocity of the c.m. system of fragments indicate that high longitudinal momentum transfer to the target is characteristic for this reaction channel. The data are consistent with the assumption that at the energy used in this experiment the projectile is stopped in the target nucleus.

I. INTRODUCTION

The production of low energy light fragments (with typical atomic numbers $3 \leq Z \leq 26$) is a phenomenon characteristic of interactions induced by intermediate and high energy projectiles. These fragments are considered to be the products of target fragmentation, in contrast to the light fragments, with velocities close to the beam velocity, which are the products of projectile fragmentation. Target fragmentation has been studied mainly in inclusive experiments.[1–11,33] Only recent experiments at high energies[12,13] provided the detection of light fragments in coincidence with the fast light particles. The mechanism (or mechanisms) of the production of low energy light fragments is not explored and understood enough. Various theoretical assumptions have been made to explain this process. In most of the theoretical considerations, the formation of an equilibrated hot zone was supposed. In this way the production of light fragments was explained by emission from a thermal source.[14–19,32] Relying on the experimentally obtained light fragment mass yields in high energy proton-induced interactions, the Purdue-Fermilab collaboration[3] proposed a connection between light fragment production and the liquid-gas phase transition in nuclear matter. The target fragmentation has more recently been interpreted in this manner by others as well.[16–19] A different interpretation of the fragmentation process is based on a model[20,21] in which the fragments are supposed to be the products of the cold, nonequilibrium breakup of spectator residues. It was assumed that the nucleons from the initial fireball enter the cold spectator matter and deposit energy and momentum. This leads to a global destabilization of the spectator matter and finally to its breakup.

At intermediate energies, the emission of low energy light fragments was examined in some recent studies.[7–11] The results of these inclusive measurements were mainly analyzed assuming the emission from a thermal source.[8,9,11] Comparison with the cold breakup model has been made by Fields *et al.*[10] It was established that the exclusive measurements of light fragments and heavy residues or target remnants are necessary for a better understanding of the fragmentation process.

In our experiment we studied the production of nuclei with atomic numbers $5 \leq Z \leq 26$ in the interaction between 84 MeV/nucleon ^{12}C and a ^{208}Pb target by using a CR-39 plastic track detector. Our experimental setup permitted us to study the correlated production of all fragments, in 4π geometry, with atomic numbers $Z \geq 5$ in a single interaction.

In this way it was proved that the light fragments originate mainly from binary breakup. We have measured the atomic numbers, angular distribution, and distribution of energy per nucleon (velocity) of light fragments with atomic numbers $5 \leq Z \leq 26$ and their corresponding heavy partners. The results of these measurements are presented and compared with the predictions of some theoretical models. The data concerning linear momentum transfer are also presented and discussed.

II. EXPERIMENT

In our experiment we used the stacks arranged as shown in Fig. 1. The ^{208}Pb target (97.69% isotopically enriched) was vacuum evaporated on sheets of a CR-39 detector (produced by Homolite Wilmington). 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 the reaction products in 4π geometry. The dimensions of the

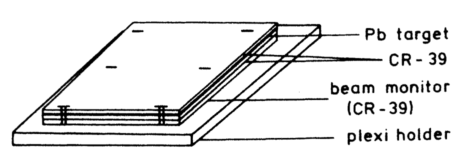

FIG. 1. Schematic diagram of the stack.

CR-39 sheets used were $50\times50\times0.5(1)$ mm. The thicknesses of the lead target varied from stack to stack between 0.7 and 0.8 mg/cm^2. To prevent a change in the recording properties of CR-39 due to high temperatures, the cooling of the detector sheets was applied during the evaporation of the target layers. The third sheet of CR-39 was used as a beam monitor. The detector sheets were mounted on a plexy holder with six screws (1 mm) and because of that they could be put back in the same position after track etching. In this way the correlation between emitted fragments was preserved.

The prepared stacks were irradiated with a normal incident 84 MeV/nucleon carbon beam at the CERN-SC (Geneva). The total number of incident particles varied between $(0.35-1)\times10^7$ for different stacks. The uncertainty in the beam intensity determination was $\sim7\%$.

After irradiation the target layers were removed by dissolving in 30% HNO_3. The track etching was carried out in 6.25N NaOH at 70 °C in a mechanically stirred bath. We employed the method of successive etching. The durations of the etching periods were 1, 3, and 5 h. The parameters of the tracks of heavy products (such as fission fragments, heavy fragmentation partners, or spallation residues) were measured after 1 h of etching. The measurements on the tracks of light products (for example, light fragmentation partners) were mostly done after 3 or 5 h of etching. Such durations of etching periods were chosen to get fully developed (finished) tracks so that the method of identification of fragments described in Ref. 22 could be applied.

Scanning and measurements have been done with an optical microscope under magnification of 53×8 and 100×8, respectively. Our scanning revealed the following types of events: (1) events characterized by the presence of one target fragment in the exit channel, (2) events characterized by the presence of two correlated target fragments, (3) events characterized by the presence of three target fragments in correlation. The projectilelike fragments were observed after 3 or 5 h of etching because of their large track induction time (Tind).[23] The projectilelike fragments with $Z\geq3$ were observable in our experment.

From the measured parameters of the finished tracks the range (R), mean etch rate ratio ($\overline{V_T/V_B}$), 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 ($\overline{V_T}$) 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 $\overline{V_T/V_B}$, the atomic number (Z) and the energy per nucleon (E/A) of products were determined as described in Ref. 22. Essentially, the method is equivalent to the experiments using ΔE and E counters which allow the determination of the Z and E of fragments. The available charge resolution according to the calibration results (taking into account errors in the determination of R and $\overline{V_T/V_B}$) was $\Delta Z\leq1$ for fragments with $Z<30$, $\Delta Z\leq2$ for heavier fragments with energy $E/A>0.5$ MeV, and $\Delta Z\leq4$ for heavy fragments with energy $E/A\leq0.5$ MeV. The maximum error in the determination of angle θ was 5 deg; on an average, this error was ~2 deg. The classification of events in different reaction channels was made after the product identification using criteria based on the characteristics of observed target products.

Due to the detector characteristics and the etch conditions used in our experiment, the protons and ions with $Z=2$ having an energy per nucleon $(E/A)>2.5$ MeV did not give observable tracks in CR-39. Also, very peripheral interactions resulting in targetlike fragments with extremely small energy could not be observed. For other reaction products there was a decrease in detection efficiency in the vicinity of the angle of 90 deg with respect to the beam direction. There are two reasons for this: thickness of the ^{208}Pb target used and the "critical angle"[24] of the incoming product. The influence of target thickness on the detection efficiency is strongest for low energy ions. For the thicknesses of targets used in this experiment the detection efficiency at an angle of 85 (and 95 in the case of detection in 4π geometry) deg was about 37% for ions with $E/A=0.1$ MeV. At the same angle the efficiency was 100% for products with energy $E/A\geq0.4$ MeV.

The fission fragments, spallation residues, and heavy fragmentation partners have critical angles at 0–2 deg with respect to the detection surface, i.e., 88–90 (and 90–92) deg with respect to the beam direction. For the light fragmentation products (i.e., products with atomic numbers $5\leq Z\leq26$) in the energy region relevant to our experiment ($0<E/A\leq6$ MeV), the critical angles varied between 85–89 (and 91–95) deg depending on their energy and atomic numbers. Taking into account the experimentally obtained energy and angular distribution of products, it can be shown that a maximum 10% of the emitted spallation and a few percent of fragmentation and fission products were undetected because of their stopping in the target and the critical angle effect. In any case, the uncertainties in our results due to losses of reaction products in the target and critical angles are small in comparison with other uncertainties.

III. RESULTS AND DISCUSSION

Our results directly show that in the interaction of 84 MeV/nucleon ^{12}C with ^{208}Pb, target fragments with atomic numbers $5\leq Z\leq26$ predominantly originate from binary breakup. The measurements revealed that a fragment with $5\leq Z\leq26$ was always accompanied by one heavy fragment ($36\leq Z\leq77$), except in a very limited number of cases when two light target fragments ($3\leq Z\leq20$) were found in correlation with one heavy fragment ($30\leq Z\leq70$). Two groups of binary events with atomic numbers of lighter fragments $Z=24$–26 were observed. One group fulfilling the kinematical requirements for fission was classified in this reaction channel, and the other group not fulfilling these conditions was taken as a contribution from the fragmentation process. The analysis included 750 binary fragmentation events with the atomic numbers of lighter products $5\leq Z\leq26$. The measured cross section for production of such events was $\sigma_F=830\pm70$ mb (or about 20% of the total reaction cross section). According to our results, the events with three correlated target fragments with $Z\geq3$ contribute to the total reaction cross section by less than 1%. These ternary events were omitted from our further analysis because of poor statistics. The projectilelike fragments were not observed in correlation with events characterized by the presence of target fragments with $5 \leq Z \leq 26$.

The counter experiment of Lynen *et al.*[7] indicated that the fragments with $6 \leq Z \leq 20$ from interactions of 85 MeV/nucleon ^{12}C with gold originate from binary breakup and that the probability of multifragmentation is below 5%. This is directly proved in our exclusive experiment. The probability of producing more than two target fragments, as mentioned in the same paper, seems to be higher for lighter targets. Also, according to Ref. 25, several medium-size fragments ($2 \leq Z \leq 8$) are emitted in the central collisions of 55–110 MeV/nucleon ^{12}C with AgBr (nuclear emulsion). In connection with that we want to point out that there is a similarity of these data with the ones obtained for interactions induced by high energy protons[26] and α particles.[27] Namely, it has been noticed that the ratio of ternary to binary events (T/B) in the above interactions[26,27] increases with decreasing target atomic number. It indicates, in our opinion, that the probability of multifragmentation is not determined by the total energy in the entrance channel or the energy per nucleon of the projectile; it is determined by the energy per nucleon available to the whole system. More data from experiments using other projectiles at various energies are necessary to prove this statement. They can offer useful information for theoretical studies regarding characteristics of nuclear matter and its breaking point.

The light fragment charge distribution obtained in our experiment is presented in Fig. 2. The average values of the nuclear charges of heavy fragmentation partners (Z_H) are presented in Fig. 3 as a function of the nuclear charge of corresponding light fragments (Z_L).

We compared the data (Fig. 2) with the power function $A^{-\tau}$ and with the exponential function B^A, assuming that an average mass number $A = 2Z_L$ corresponds to the fragment atomic number Z_L. The simple expression $Y(A) \propto A^{-\tau}$ has been used extensively to describe the yield of intermediate mass fragments from high energy proton and heavy ion induced reactions. Typical values of the exponent found in fitting the data were 2–3. Some authors[4–19] claimed that this indicates the condensation as a production mechanism, since, according to the theory of the liquid-vapor transition,[28] the distribution of cluster sizes should obey a power law whose exponent is between 2 and 3. Our best fit gave the value $\tau = 1.97$. However, as can be seen in Fig. 2, such a power law distribution does not describe the experimental data better than the exponential function B^A ($B = 0.93 \pm 0.01$).

We fitted our data according to the formula given in the cold breakup of spectator residue calculations[21] as well. The average sum of the atomic numbers of light and heavy fragments ($Z_0 = Z_L + Z_H$) was used as the spectator atomic number (Z_0). The obtained value of the total fragmentation cross section was $\sigma = 227$ mb. It is considerably smaller than the value of the measured fragmentation cross section $\sigma_F = (830 \pm 70)$ mb. It can also be seen (Fig. 2) that the power function ($A^{-\tau}$) and the cold breakup of spectator residue calculations overestimate cross sections of lighter elements. This is understandable bearing in mind the fact that the multiplicity of fragments is not limited in these calculations and that the measured fragments originate from the binary breakup. The smaller than theoretically assumed multiplicity of emitted fragments can perhaps explain the unrealistic small values of the charge (Z_0) of the target spectator obtained by comparison of the data from the 30 MeV/nucleon $^{12}C + ^{197}Au$ interaction[10] with the cold breakup of the spectator residue model.

The difference (ΔZ) between the sum of the atomic numbers of projectile and target and the sum of the atomic numbers of light and heavy fragmentation partners [$\Delta Z = (Z_p + Z_T) - (Z_H + Z_L)$] represents the sum of the charge numbers of emitted light particles (protons, α particles). They can be emitted before, during, and after the binary breakup. In the case of peripheral collisions, ΔZ

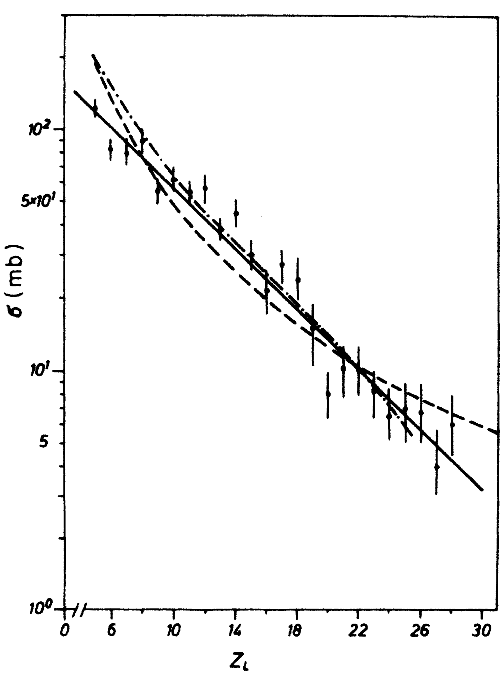

FIG. 2. Charge distribution of light fragments obtained in our experiment. The full line is a comparison with the exponential function B^A; the dashed curve is a comparison with the power law $A^{-\tau}$; the dashed-dotted curve is a comparison with the cold spectator breakup calculations (Ref. 21).

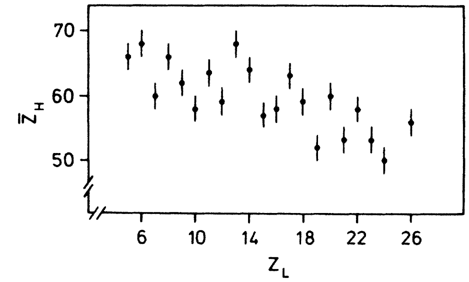

FIG. 3. Average values of the atomic numbers of heavy fragmentation partners (Z_H) plotted versus the atomic numbers of corresponding light fragments (Z_L).

TABLE I. The average values (ΔZ) of the sum of the charge numbers of emitted light particles (protons, α particles).

Light fragments atomic number (Z_L)	ΔZ
5	16
6	14
8	14
$10 \leq Z_L \leq 14$	14
$15 \leq Z_L \leq 26$	10

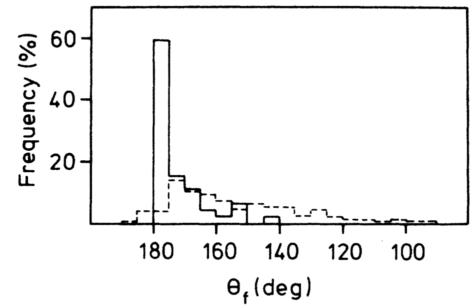

FIG. 4. Distribution of folding angles for fragmentation events: — — —, with respect to the beam direction; ——, in the plane normal to the beam direction.

would include, also, the atomic number of the projectile-like fragment but, as previously mentioned, the fragmentation events, examined in our experiment, were not accompanied by projectilelike fragments. The average values of ΔZ for various atomic numbers of emitted light fragments (Z_L) are given in Table I.

The folding angles between fragmentation partners with respect to the beam direction are given by $\theta_L + \theta_H$, where θ_L and θ_H are the emission angles of light and heavy fragments, respectively. The folding angles in the plane normal to the beam direction were also measured. Figure 4 shows the distributions of folding angles obtained in our experiment.

The distribution of folding angles between the correlated fragments represents, in a first approximation, the distribution of the velocities (momenta) of the emitting (c.m.) system of fragments. As can be seen in Fig. 4, the distribution of folding angles in the plane normal to the beam direction has a peak around 180—175 deg and is narrower than the distribution of folding angles with respect to the beam direction. It means that the transverse momentum (velocity) of the c.m. system of light and heavy fragments is relatively small compared to its longitudinal momentum (velocity).

To calculate the longitudinal component ($\beta_{\parallel}$) of the velocity of the c.m. system of light and heavy fragments, the following relations based on momentum conservation were used:

$$A_L = 2Z_L \; , \quad (1)$$

$$A_H = [(Z_L + Z_H)/(Z_p + Z_t)](A_p + A_t) - A_L \; , \quad (2)$$

$$[(A_L/(A_L + A_H)](P/A)_L \cos\theta_L + [A_H/(A_L + A_H)](P/A)_H \cos\theta_H = P_0 \; , \quad (3)$$

$$\beta_{\parallel} = P_0/m_n \; . \quad (4)$$

A_L and A_H denote the mass numbers of light and heavy fragmentation partners, respectively; $(P/A)_L$ and $(P/A)_H$ denote the linear momenta per nucleon of fragments obtained from their energies per nucleon $(E/A)_L$ and $(E/A)_H$, respectively; θ_L and θ_H denote the emission angles of the fragments; P_0 denotes the longitudinal momentum per nucleon of the c.m. system of fragments; $\beta_{\parallel}$ denotes the longitudinal velocity of the c.m. system; and $m_n = 931.481$ MeV.

The calculated values of $\beta_{\parallel}$ are not very sensitive to the assumptions about the mass numbers of fragments made in relations (1) and (2). Changing the A_H values by 20% would modify the value of $\beta_{\parallel}$ by less than 7%.

The distribution of the longitudinal velocity ($\beta_{\parallel}$) of the c.m. system of fragments is presented in Fig. 5. For the sake of comparison, the longitudinal velocity of the fission c.m. systems is also shown in the same figure.

Galin *et al.*[29] inferred from their fission studies and low energy proton emission data that, generally, in the interactions induced by 15—84 MeV/nucleon ^{12}C ions the transferred longitudinal momentum does not exceed 2 GeV/c. This fact has been used to suggest[30] that this limitation is evidence for soliton formation in heavy ion interactions near the velocity of sound in nuclear matter. On the other hand, Kowalski *et al.*[31] suggested that the observed limiting momentum transfer appears as a natural consequence of the transition from the peripheral to the more central collisions, i.e., that the limitation is observed in the measurements of reaction products originating from the peripheral collisions. The most probable momentum transfer, measured in our experiment, for the fission process was also around 2 GeV/c. We have found

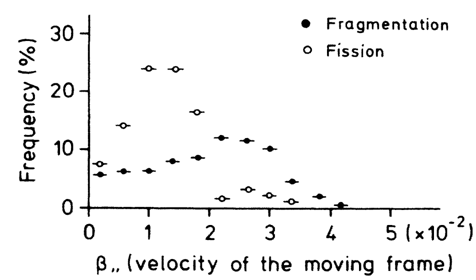

FIG. 5. Distributions of the longitudinal velocity of the c.m. system of fragments for fragmentation and fission.

that the sum of the atomic numbers of fission fragments is on an average less than 10% larger than the sum of the atomic numbers of fragmentation partners. Therefore, our results presented in Fig. 5 directly show that the target fragmentation corresponds to the higher linear momentum transfer. The limitation observed for the fission reaction channel does not exist for the fragmentation reaction channel.

The average values of $\beta_{\|}$ for fragmentation events with different light fragment atomic numbers are presented in Table II. The distributions of $\beta_{\|}$ for fragmentation events with $Z_L=5$ and $10 \le Z_L \le 14$ are shown in Fig. 6. It can be seen that $\beta_{\|}$ is dependent on the atomic number of the light fragment. The longitudinal velocity of the c.m. system of fragments decreases with an increase of the light fragment atomic number. The average value of $\beta_{\|}$ for events with $Z_L=5$ is nearly equal to the velocity ($\beta_{\|}=0.0232$) of the nucleus-nucleus (projectile-target) c.m. system. The angular distributions of light and heavy fragmentation partners in the nucleus-nucleus c.m. system are shown in Fig. 7. It can be seen that the emission of fragments is anisotropic in this system.

Distributions of the laboratory energy per nucleon (E/A) of light fragments with $Z_L=5$, $Z_L=8$, and $10 \le Z_L \le 14$, and of their corresponding heavy partners, are presented in Figs. 8(a) and 8(b), respectively. The peak in the light fragment energy distribution is usually connected, in the analysis of experimental results, with an effective Coulomb repulsion energy $B_{\rm eff}=kB_{\rm nom}$, where $B_{\rm eff}$ corresponds to the experimentally determined peak position; k (<1) is the reduction factor; and $B_{\rm nom}$ is the nominal Coulomb barrier. Conventionally, $B_{\rm nom}$ is calculated assuming that the system splits into two spherical nuclei (one of which is the fragment and the other the heavy residue) following light particle (nucleon) emission in the initial interaction between the target and the projectile. The k values obtained in various experiments varied between 0.1 and 0.5. We obtained the value $k \approx 0.4$ from the light fragment energy distribution in the c.m. system of fragments.

On the other hand, the influence of Coulomb repulsion on the energies of heavy fragmentation products is very small. Possible contribution of the nominal (tangent sphere) Coulomb potential to the energy corresponding to the peak positions of the distributions presented in Fig. 8(b) is about 10%. The longitudinal linear momentum of heavy fragmentation partners is given by

$$P_{Hl}=(P/A)_H A_H \cos\theta_H \ ,$$

TABLE II. The average longitudinal velocity ($\beta_{\|}$) of the c.m. system of fragments.

Light fragments atomic number (Z_L)	$\beta_{\|}$
5	0.0238±0.0020
8	0.0189±0.0020
$10 \le Z_L \le 14$	0.0142±0.0020
$15 \le Z_L \le 26$	0.0125±0.0016

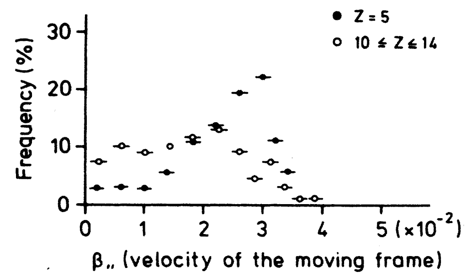

FIG. 6. Distribution of the longitudinal velocity of the c.m. system of fragments for fragmentation events with light fragments with atomic numbers $Z=5$ and $10 \le Z \le 14$.

where $(P/A)_H$ and θ_H are the experimentally measured linear momentum per nucleon and the emission angle with respect to the beam direction, respectively, and A_H is the mass number of the heavy fragmentation partner. We calculated P_{Hl} assuming that the heavy fragment atomic number Z_H corresponds to the mass number (A_H) of the most stable isotope. This brings uncertainties in the P_{Hl} values of about 10%. The results obtained have shown that the average longitudinal linear momenta of heavy products whose light partners have atomic numbers $Z_L=5$ and $15 \le Z_L \le 26$ are $P_{Hl}=2330$ MeV/c and $P_{Hl}=1460$ MeV/c, respectively, i.e., about 50% and 30% of the incident linear momentum.

If the fragmentation process is a result of the cold breakup of spectator residues, as proposed by Aichelin *et al.*,[21] then the spectator size in the interaction examined in this experiment is represented by $Z_0=Z_L+Z_H$ (we have already used this expression in the light fragment cross section calculations). But, if the light fragments are emitted from the hot zone, then the heavy fragmentation partner (Z_H) corresponds to the spectator residue. Can the relatively large longitudinal linear momentum of the spectator measured in this experiment [according to the first model represented by the longitudinal velocity of the c.m. system of fragments ($\beta_{\|}$) and according to the second model by the longitudinal linear momentum of the heavy fragmentation partner] be explained only by the absorption of a few nucleons from the hot zone, as supposed in some theoretical studies,[21,34] or perhaps, by the collective transfer of momentum? In any case, taking into account the law of linear momentum conservation, the larger longitudinal linear momentum of the spectator means that the lower amount of the longitudinal linear

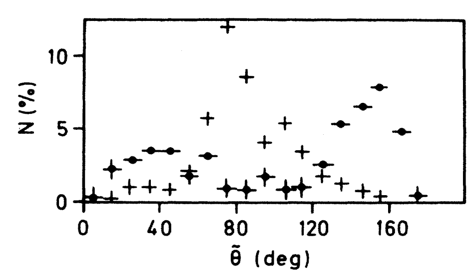

FIG. 7. Angular distributions of light (●) and heavy (+) fragmentation partners in the nucleus-nucleus c.m. system.

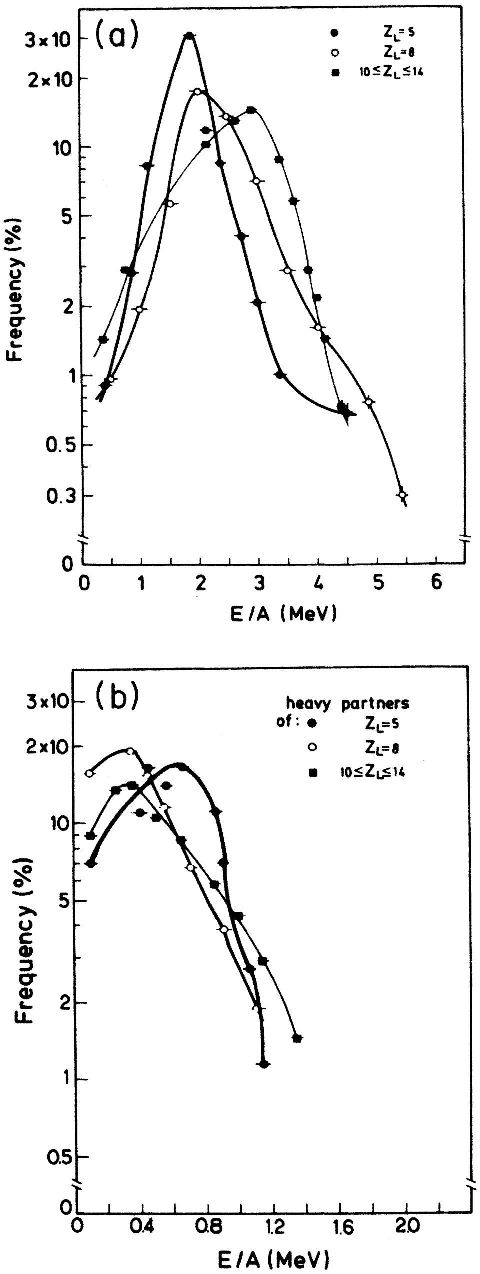

FIG. 8. (a) Distributions of the energy per nucleon (E/A) for fragments with atomic number $Z_L=5$, $Z_L=8$, and $10 \leq Z_L \leq 14$. (b) Distributions of the energy per nucleon (E/A) for heavy fragments observed in correlation with fragments with $Z_L=5$, $Z_L=8$, and $10 \leq Z_L \leq 14$, respectively. The solid lines are drawn to guide the eye.

momentum is taken away by the emitted light particles. This indicates that, at the energy used in this experiment, the projectile is stopped inside the target nucleus. The nucleons from the participant zone, therefore, cannot be emitted in the forward direction without passing through the spectator matter, which decreases their velocity. A similar conclusion, but drawn on the basis of different facts, was reached in theoretical considerations by Aichelin *et al.*[21]

Some interesting questions also arise from the observed dependence of measured parameters on the atomic number (Z_L) of light fragments. It has been supposed, until recently, that the emission of light fragments, independent of their mass, is simultaneous. But, Boal[35] suggested that the time of light fragment emission from the hot zone could be a function of the fragment mass. As a possibility to explain the experimentally observed decrease in the source temperature with the increase of light fragment mass, he proposed a picture of a source increasing by accretion of nucleons. According to the same study,[35] there should be much less accretion in the nucleus-nucleus interactions than in the proton-induced interactions. From our experimental results the upper limit of the charge (Z_{SL}) of the light fragment source can be calculated as

$$Z_{SL}=Z_p+Z_T-Z_H=\Delta Z+Z_L$$

(Z_{SL} is equal to the charge of the source in the case that there is no emission of charged particles from the heavy fragmentation partner after binary breakup). Assuming that in the source the proton to neutron ratio for nucleons originating from the target is the same as in the target, the upper limit of the source size is given by

$$A_{SL}=A_p+(Z_S-Z_p)(A_T/Z_T) .$$

So, the calculated upper limit of the source size increases from $A_{SL} \approx 50$ to $A_{SL} \approx 90$ nucleons in the region of the fragment atomic numbers from $Z_L=5$ to $Z_L=26$. The temperature (T) of an ideal Fermi gas at normal density formed by the fusion between projectile and ($A_{SL}-A_p$) target nucleons decreases from about $T=11$ MeV to $T=9$ MeV in the same region of Z_L.

The decrease of the longitudinal velocity of the c.m. system of fragments ($\beta_{\parallel}$) with light fragment atomic number (Z_L) (see Table II) can be tentatively explained by the different impact parameters in the projectile-target initial collision. But this behavior can be also explained, independent of the mechanism of the process, by different numbers of nucleons emitted before binary breakup. It seems reasonable to assume that the nucleons emitted before binary breakup have higher energies and different angular distribution than the nucleons emitted after binary breakup. If more nucleons are emitted before the emission of light fragments, then more energy (momentum) is taken away from the system. This results in smaller values of the velocity ($\beta_{\parallel}$) of the c.m. system of fragments. After binary breakup the nucleons are emitted from the excited fragments. It can be supposed that the fragments cool down by evaporation of nucleons, which affects their momenta, but not their velocities much. The fragments will be more excited and evaporate more nucleons if the number of nucleons emitted before the binary breakup is smaller. In the case that the former discussion is correct, the multiplicity of the high energy nucleons should increase and the multiplicity of the low energy nucleons should decrease with an increase of Z_L. The measurements which would give the number, energy, and angular distribution of emitted nucleons correlated with the mass of emitted fragments are necessary to reach any definite conclusion about the connection of the time of emission with the mass of light fragments.

IV. CONCLUSION

Our results directly show that the production of fragments with atomic numbers $5 \leq Z_L \leq 26$ in the interaction of 84 MeV/nucleon ^{12}C with a ^{208}Pb target is a binary process. The contribution of multifragmentation is less than 1% of the total reaction cross section.

The distribution of the longitudinal velocity of the c.m. system of fragments obtained in our experiment does not indicate the presence of limitation in the transfer of linear momentum for the fragmentation reaction channel. The high values of the longitudinal velocity of the c.m. system of fragments and of the longitudinal linear momentum of the heavy fragmentation partner indicate that, at the energy used in this experiment, the projectile is stopped in the target nucleus.

The dependence of the measured parameters on the atomic number of the light fragmentation partner is observed. This suggests that the emission of light fragments is not simultaneous, i.e., that the fragments with higher atomic numbers are emitted later than the fragments having lower atomic numbers.

ACKNOWLEDGMENTS

We are very grateful to Dr. Allardice and the operating crew at the CERN-SC for their help during irradiations. We are also indebted to Dr. Folger (GSI) for preparation of the targets. Discussions with Professor Porile (Purdue) are appreciated. This work was supported by the BMFT (Bonn).

*Present address: Farbwerke Bayer AG, Leverkusen, Federal Republic of Germany.

[1]A. M. Poskanzer, G. W. Butler, and E. K. Hyde, Phys. Rev. C 3, 882 (1971).

[2]J. Gosset, H. H. Gutbrod, W. G. Meyer, A. M. Poskanzer, A. Sandoval, R. Stock, and G. D. Westfall, Phys. Rev. C **16**, 629 (1977).

[3]J. E. Finn, S. Agarwal, A. Bujak, J. Chuang, L. J. Gutay, A. S. Hirsch, R. W. Minich, N. T. Porile, R. P. Scharenberg, B. C. Stringfellow, and F. Turkot, Phys. Rev. Lett. **49**, 1321 (1982).

[4]A. S. Hirsch, A. Bujak, J. E. Finn, L. J. Gutay, R. W. Minich, N. T. Porile, R. P. Scharenberg, and B. C. Stringfellow, Phys. Rev. C **29**, 508 (1984).

[5]G. D. Cole and N. T. Porile, Phys. Rev. C **24**, 2038 (1981).

[6]R. W. Stoenner, P. E. Haustein, and J. B. Cumming, Phys. Rev. Lett. **53**, 341 (1984).

[7]U. Lynen, H. Ho, W. Kühn, D. Pelte, U. Winkler, W. F. J. Müller, Y-T. Chu, P. Doll, A. Gobbi, K. Hildebrand, A. Olmi, H. Sann, H. Stelzer, R. Bock, H. Löhner, R. Glasow, and R. Santo, Nucl. Phys. **A387**, 129C (1982).

[8]C. B. Chitwood, D. J. Fields, C. K. Gelbke, W. G. Lynch, A. D. Panagiotou, M. B. Tsang, H. Utsunomiya, and W. A. Friedman, Phys. Lett. **131B**, 289 (1983).

[9]B. V. Jacak, G. D. Westfall, C. K. Gelbke, L. H. Harwood, W. G. Lynch, D. K. Scott, H. Stöker, and M. B. Tsang, Phys. Rev. Lett. **51**, 1846 (1983).

[10]D. J. Fields, W. G. Lynch, C. B. Chitwood, C. K. Gelbke, M. B. Tsang, H. Utsunomiya, and J. Aichelin, Phys. Rev. C **30**, 1912 (1984).

[11]B. Borderie, M. F. Rivet, C. Cabot, D. Fabris, D. Gardes, H. Gauvin, F. Hanappe, and J. Peter, Z. Phys. A **318**, 315 (1984).

[12]W. G. Meyer, H. H. Gutbrod, Ch. Lukner, and A. Sandoval, Phys. Rev. C **22**, 179 (1980).

[13]A. I. Warwick, H. H. Wieman, H. H. Gutbrod, M. R. Maier, J. Péter, H. G. Ritter, H. Stelzar, and F. Weick, Phys. Rev. C **27**, 1083 (1983).

[14]D. H. E. Gross, L. Satpathy, M. Ta-Chung, and M. Satpathy, Z. Phys. A **309**, 41 (1982).

[15]W. Friedman and W. G. Lynch, Phys. Rev. C **28**, 950 (1983).

[16]M. W. Curtin, H. Toki, and D. K. Scott, Phys. Lett. **123B**, 289 (1983).

[17]A. D. Panagiotou, M. W. Curtin, H. Toki, D. K. Scott, and P. J. Siemens, Phys. Rev. Lett. **52**, 496 (1984).

[18]A. L. Goodman, J. I. Kapusta, and A. Z. Mekjian, Phys. Rev. C **30**, 851 (1984).

[19]A. D. Panagiotou, M. W. Curtin, and D. K. Scott, Phys. Rev. C **31**, 55 (1985).

[20]J. Aichelin and J. Hüfner, Phys. Lett. **136B**, 15 (1984).

[21]J. Aichelin, J. Hüfner, and R. Ibarra, Phys. Rev. C **30**, 107 (1984).

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

[23]B. Grabež, P. Vater, and R. Brandt, Nucl. Tracks **5**, 291 (1981).

[24]R. L. Fleisher, P. B. Price, and R. M. Walker, *Nuclear Tracks in Solids: Principles and Applications*, 1st ed. (University of California Press, Berkeley, 1975), pp. 58–60.

[25]B. Jakobsson, G. Jönsson, B. Lindkvist, and A. Oskarsson, Z. Phys. A **307**, 293 (1982).

[26]G. Remy, J. Ralarosy, R. Stein, M. Debeauvais, and J. Tripier, J. Phys. (Paris) **31**, 27 (1970).

[27]B. Grabež, Z. Todorovič, and R. Antanasijevič, Nucl. Instrum. Methods **147**, 267 (1977).

[28]M. E. Fisher, Physics (N.Y.) **3**, 255 (1967).

[29]J. Galin, H. Oeschler, S. Song, B. Borderie, M. F. Rivet, I. Forest, R. Bimbot, D. Gardés, B. Gatty, H. Guillemot, M. Lefort, B. Tamain, and X. Tarrago, Phys. Rev. Lett. **48**, 1787 (1982).

[30]G. N. Fowler, S. Raha, N. Stelte, and R. M. Weiner, Phys. Lett. **115B**, 286 (1982); S. Raha and R. M. Weiner, Phys. Rev. Lett. **50**, 407 (1983).

[31]L. Kowalski, P. E. Haustein, and J. B. Cumming, Phys. Rev. Lett. **51**, 642 (1983).

[32]L. G. Moretto, Nucl. Phys. **A247**, 211 (1975).

[33]L. G. Sobotka, M. L. Padgett, G. J. Woznaik, G. Guarino, A. J. Pacheco, L. G. Moretto, Y. Chan, R. G. Stokstad, I. Tserruya, and S. Wald, Phys. Rev. Lett. **51**, 2187 (1983).

[34]A. O. T. Karvinen, J. N. De, and B. Jakobsson, Nucl. Phys. **A367**, 122 (1981).

[35]D. H. Boal, Phys. Rev. C **30**, 119 (1984).