TARGET MASS DEPENDENCE OF THE Pb PROJECTILE FRAGMENTATION AT 158 $\boldsymbol{A}$ GeV

A. Dąbrowska, M. Szarska, A. Trzupek, W. Wolter and B. Wosiek

Henryk Niewodniczański Institute of Nuclear Physics
Radzikowskiego 152, 31-342 Kraków, Poland

(Received April 17, 2002)

Fragmentation of 158 A GeV Pb nucleus after the collision with Pb and plastic targets has been studied using several lead-emulsion chambers irradiated in SPS at CERN. It was found that more than 50% of Pb+Pb interactions at 158 A GeV are of electromagnetic origin. The distributions of the number of fragments are target dependent while their charges and the shapes of their angular distributions are independent of the target mass. For a given energy transferred to the spectator part of the nucleus the mean values of the number of fragments and their charges as well as angular distributions are the same for light and heavy targets, except for the most central collisions.

PACS numbers: 25.75.+r, 29.40.Rg

1. Introduction

Since many years the process of nuclear fragmentation has been investigated employing different experimental techniques: nuclear emulsion, plastic detectors, electronic and hybrid experiments. Despite the numerous experimental and theoretical approaches to the study of fragmentation phenomena, using different projectiles at different energies and variety of targets, the process of nuclear fragmentation is far from being well understood. The reason for this is the complexity of the process of nuclear fragmentation manifested itself in a variety of fragmentation modes. Therefore, it is desirable to continue investigations in this field in order to collect more data especially in the region of the highest available energies.

This paper is a continuation of our analysis [1, 2] of interactions of 158 A GeV lead nuclei with lead and plastic ($C_5H_4O_2$) targets. In the present paper we concentrate on the analysis of general properties of fragmentation of Pb projectile nucleus after the collision with heavy and light targets. The analyzed data were obtained from the CERN EMU13 experiment in which lead-emulsion chambers were exposed to the beam of ^{208}Pb ions accelerated in SPS.

The paper is organized as follows: In Sec. 2 a short description of the experiment is given. A unique composition of lead-emulsion chambers used in this experiment enabled to perform a precise angular measurements of singly and multiply charged fragments with the simultaneous measurements of their charges. In Sec. 3 our scanning efficiency for Pb interactions with plastic and lead targets is discussed together with the estimation of the cross-section for electromagnetic interactions in the high energy Pb+Pb interactions. The charge and multiplicity distributions of projectile fragments are presented in Sec. 4. Angular distributions of fragments in collisions of lead with lead and plastic targets and their relation to the energy transferred to the spectator part of the projectile nucleus are presented in Sec. 5. Sec. 6 gives the summary.

2. Experiment

Lead-emulsion chambers were exposed to the beam of 158 A GeV lead ions ($A = 208$) at the CERN SPS. The chambers were composed of three segments: the target section with lead sheets interleaved with emulsion coated double side on acrylic plates, the angular measurement segment composed of plastic emulsion plates with spacers of increasing thickness downstream, and the charge measurement segment composed of 500 μm thick emulsion pellicles. Details of the lead-emulsion chambers used in this EMU 13 experiment as well as irradiation conditions can be found elsewhere [1, 3, 4]. Scanning for Pb+Pb and Pb+PL[1] interactions was carried out under the microscope in the target segment of lead-emulsion chambers. Details of scanning were described in [1].

Angular measurements of particles emitted from the interaction vertex was done within the cone of 10 mrad of the half opening angle. Within this cone all spectator protons, multiply charged fragments and some produced particles are contained. Measurements were done with the CCD camera mounted on the microscope and coupled to the computer. δ-ray counts were used to evaluate the charge of fragments. These measurements were performed in a set of thick emulsion pellicles placed at the bottom of each lead-emulsion chamber. For the details of angular and charge measurements of fragments see [1].

[1] In this paper we will use an abbreviation (PL) to denote the PLastic ($C_5H_4O_2$) target.

3. Estimation of scanning efficiency: interplay between nuclear and electromagnetic processes

Our scanning for Pb+Pb and Pb+PL interactions recorded in lead-emulsion chambers was inefficient for interactions with the charge of the heaviest fragment, Z_1, not very different from the charge of the primary nucleus. This scanning inefficiency for interactions with large Z_1 values is well seen in Fig. 1, where we plotted the yields of the heaviest fragments with the charge Z_1 in Pb+PL interactions. For the sake of clarity the widths of the bins in Fig. 1 are not uniform.

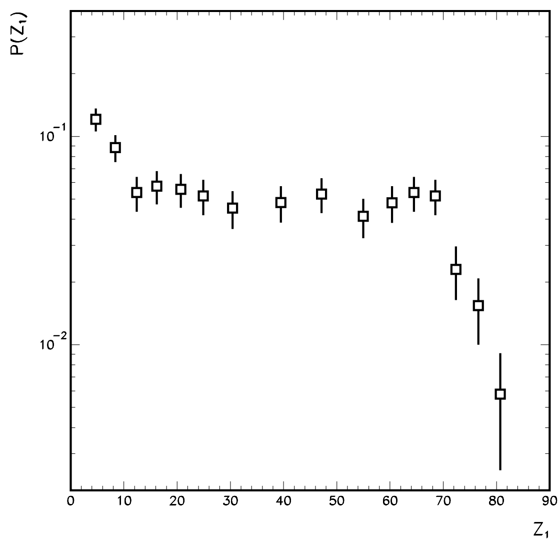

Fig. 1. Distribution of the charge Z_1 of the heaviest fragment for the measured Pb+PL interactions.

In the following we assume that below the $Z_1 = 68$ all interactions were found and that the fraction of lost events with $Z_1 \geq 68$ is the same for lead and plastic targets. In addition, contribution of electromagnetic interactions to the Pb+PL event sample was neglected. This is supported by the calculations of the electromagnetic dissociation cross-section, using the Weizsacker–Williams formalism [5], which showed that electromagnetic dissociation contributes to only few percent of the total Pb+PL cross-section.

The scanning for Pb+PL interactions resulted in 529 events (see Table I). Using $\sigma_{\rm nucl}(\text{Pb+PL}) = 2.54$ b [6] and the measured flux of Pb ions, the expected number of lead interactions with this light target should be 861. Thus, our scanning efficiency for Pb+PL interactions is about 60%. The fraction of lost events with $Z_1 \geq 68$ approaches 90%.

TABLE I

Number of measured and expected events for Pb+PL and Pb+Pb interactions with different values of the charge Z_1 of the heaviest fragment.

	Pb+PL			Pb+Pb		
	$Z_1 \geq 68$	$Z_1 < 68$	All	$Z_1 \geq 68$	$Z_1 < 68$	All
Measured events	45	484	529	29	435	464
Expected events	377	484	861	244	435	679

For Pb+Pb collisions we measured 464 events out of which 29 have $Z_1 \geq 68$ (see Table I). Applying the same correction for scanning losses as in Pb+PL collisions we get the total expected number of events of 679.

This gives the scanning efficiency of about 68% for Pb+Pb interactions. Using σ_{nucl} (Pb+Pb) = 6.36 b [7] and the measured flux of Pb ions, the expected number of Pb+Pb collisions of nuclear nature is 299, corresponding to 44% of the total expected number of events. The remaining 56% are due to electromagnetic interactions. This fraction of electromagnetic events among all charge changing interactions is consistent with the value of 53% reported in [6]. Electromagnetic events are predominantly characterized by the emission of few nucleons, thus mainly contribute to events with $Z_1 \geq 68$. However, it can be seen from Table I that there is still considerable fraction of electromagnetic events dispersed among interactions with $Z_1 < 68$, which cannot be separated from nuclear interactions.

Applying the correction for lost events with $Z_1 \geq 68$, we can only obtain the unbiased number of events with $Z_1 \geq 68$, but the detailed properties of these events remain unknown. Therefore, whenever the knowledge of precise properties of $Z_1 \geq 68$ events is not essential we present the results for the full data set corrected for scanning biases. On the contrary when the detailed properties of these events may affect the data we will restrict the presentation to events with $Z_1 < 68$. All plots, except that shown in Fig. 1, are corrected for scanning inefficiency.

4. Charge and multiplicity distributions of fragments

We begin with the study of the parameter Z_b, that is the sum of charges of all multiply charged fragments. This is an observable frequently used in experiments in which all or nearly all multiply charged fragments are observed and measured. Physically the Z_b can be considered [8] as a measure of the energy transferred to the excited spectator part of the nucleus. Larger energy transfers correspond to smaller values of Z_b.

In Fig. 2 we plotted the Z_b distributions in Pb+Pb and Pb+PL interactions. The distribution in Pb+Pb interactions is practically flat except for the largest Z_b values, while the distribution for Pb+PL interactions continuously increases with increasing Z_b, being zero for the smallest values of Z_b. This means that in Pb+PL interactions there are no events characterized by a complete disruption of the projectile Pb nucleus into singly charged spectators. The bulk ($\sim$ 50%) of Pb+Pb and Pb+PL interactions have Z_b not very different from the charge of the primary nucleus *i.e.* they are of very peripheral nature. In the case of Pb+PL collisions these are due to nuclear interactions only, while in Pb+Pb collisions both nuclear and electromagnetic interactions contribute. The most frequently observed fragments both

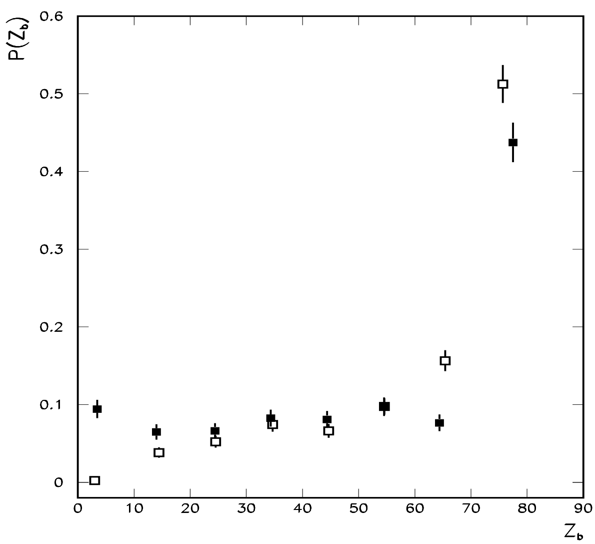

Fig. 2. Distribution of the sum Z_b of multiply charged fragments in Pb+Pb (filled squares) and Pb+PL (open squares) interactions.

in Pb+Pb and Pb+PL interactions are light and heavy fragments. The first are seen in Fig. 3 where we plotted the charge distribution of fragments with $2 < Z < 68$. Heavy fragments above $Z = 68$ cannot be plotted because their distribution is unknown. They constitute of about 40% of all fragment charges (see Table I). The enhancement of fragments with charges in the vicinity of half of the charge of the primary seen in Fig. 3 is due to fragments from fission of the projectile Pb nucleus. The charge distribution of fragments within the restricted region $2 < Z < 68$ does not show a significant dependence on the mass of the target.

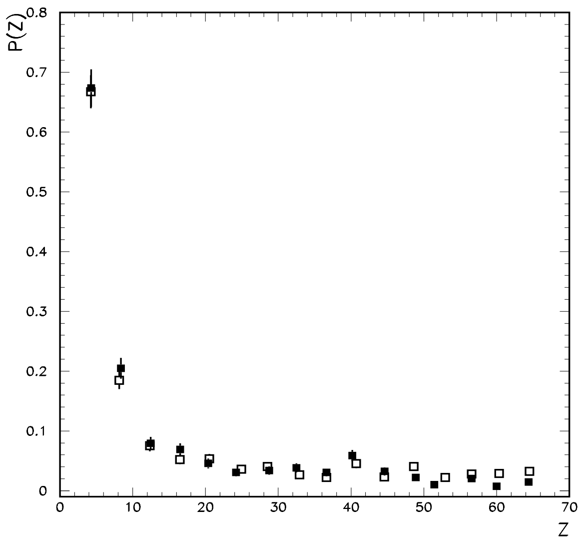

Fig. 3. Charge distribution of fragments with $2 < Z < 68$ in Pb+Pb (filled squares) and Pb+PL interactions (open squares).

In Fig. 4 the mean charges $\langle Z \rangle$ of fragments heavier than helium are plotted as a function of Z_b for Pb+Pb and Pb+PL interactions. The mean values of fragment charges must increase with increasing Z_b due to the strong correlation between these quantities. However, it should be stressed that for a given Z_b the mean values of charges of fragments do not depend on the mass of the target, except for the most peripheral Z_b bin. In other words the mean charge of fragments depends primarily on the energy transferred to the spectator part of the projectile nucleus, but not on the collision system.

The distribution of the number $N_{\rm f}$ of fragments heavier than helium (see Fig. 5) has a maximum at $N_{\rm f} = 1$. This is consistent with the large fraction of peripheral collisions both in Pb+Pb and Pb+PL interactions, and additional contribution from electromagnetic interactions in Pb+Pb events. In Pb interactions with light target there are practically no events without $N_{\rm f}$ fragments, whereas in Pb+Pb interactions in about 10% of collisions the projectile nucleus was broken into fragments not heavier than helium.

It has been customary to separate the projectile nucleus fragments into singly charged spectators, helium and heavier fragments. Experimentally it is easy to separate helium and heavier fragments of the projectile nucleus from produced particles and fragments of the target nucleus. However, this is not the case for singly charged spectators. These are singly charged relativistic particles indistinguishable from produced particles and projectile protons, which have already participated in the collision. In nuclear emulsion

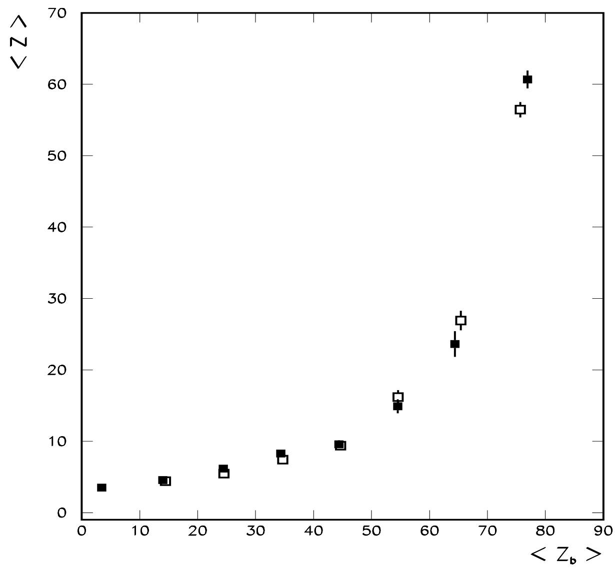

Fig. 4. Correlation between the mean charge $\langle Z \rangle$ and Z_b in Pb+Pb and Pb+PL interactions. Symbol description is the same as in Figs. 2 and 3.

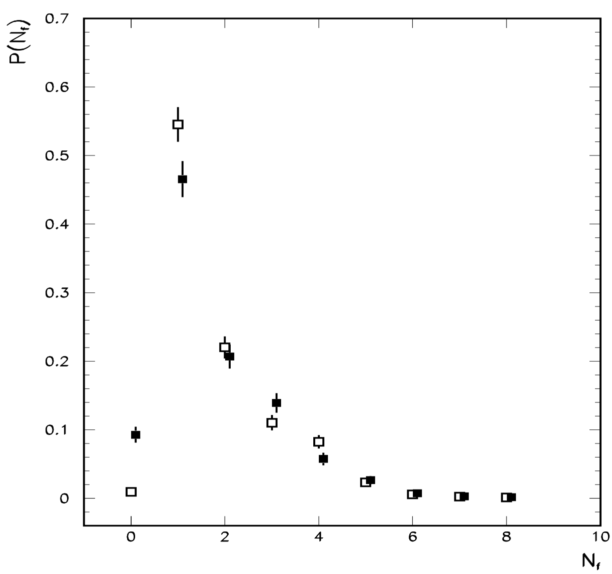

Fig. 5. Distribution of the number N_{f} of fragments in interactions of Pb+Pb and Pb+PL.

technique the only criterion which can be used to separate singly charged spectators from other singly charged relativistic particles is their small emission angle, which depends on the primary energy. From our previous studies concerning the analysis of 200 A GeV oxygen and sulfur interactions [1,9,10] we have found that within the angle of 3 mrad almost all spectator protons are contained and the number of produced particles is very small. This statement was supported by the Venus MC Model calculations. Shifting the pseudorapidity $\eta = -\ln\tan(\theta/2) = 6.5$ which corresponds to 3 mrad by $\ln(158/200)$ one gets $\eta_{\rm frag} = 6.26$ above which practically all singly charged particles are spectators in Pb interactions at 158 A GeV.

In Fig. 6 we show the dependence of the mean numbers $\langle N_{\rm sp}\rangle$, $\langle N_\alpha\rangle$ and $\langle N_{\rm f}\rangle$ of singly charged spectators, helium and heavier fragments on Z_b. The dependence for $N_{\rm f}$ fragments (Fig. 6(c)) is similar for both targets: as the energy transferred to the spectator part of the nucleus decreases the mean number of fragments increases, reaching maximum at the vicinity of $Z_b \approx Z_{\rm p}/2$, where $Z_{\rm p}$ is the charge of the projectile. For still smaller energy transfers ($Z_b > Z_{\rm p}/2$) the mean number of fragments decreases as a result of increasing charge of the heaviest fragment. For a given energy transferred

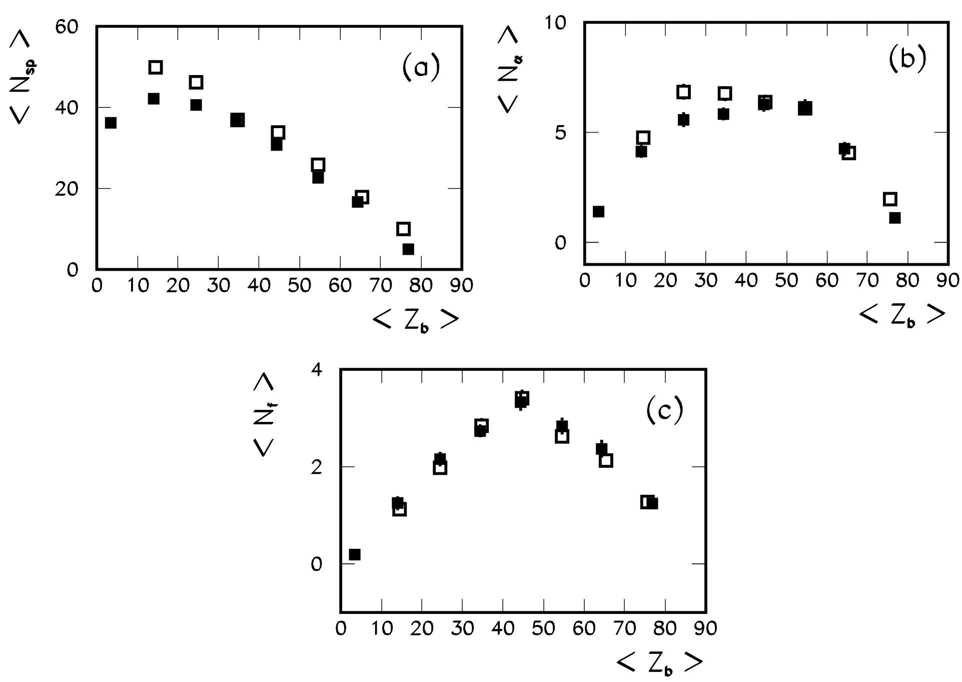

Fig. 6. Correlation between the mean numbers of singly charged spectators, $\langle N_{\rm sp}\rangle$ (a), helium, $\langle N_\alpha\rangle$ (b), and heavier, $\langle N_{\rm f}\rangle$ (c) fragments, and the Z_b for Pb+Pb and Pb+PL interactions.

to the spectator part of the projectile nucleus (the same values of Z_b), the mean number of all kind of fragments does not depend on the mass of the target nucleus. However, in collisions with the light target there is a small enhancement of helium fragments (Fig. 6(b)), mainly for relatively small Z_b values and the mean values of singly charged spectators are systematically larger than that for Pb+Pb interactions (Fig. 6(a)). It should be noticed that in Pb+PL interactions there are no events within the smallest bin of Z_b (most central events). On the other hand in most central Pb+Pb collisions ($Z_b \leq 10$) there are practically only singly charged spectators.

5. Angular distribution of fragments

In Fig. 7 the angular distributions of singly charged spectators ($\eta \geq 6.26$), helium and heavier fragments are shown as a function of $E_0 \sin\theta$, where E_0 is the projectile energy per nucleon. This variable is equivalent to the particle transverse momentum under the assumption that the momenta of fragments are the same as that of the primary nucleus. The shapes of angular distributions become narrower as the mass of fragments increases, but are roughly independent of the mass of the target nucleus.

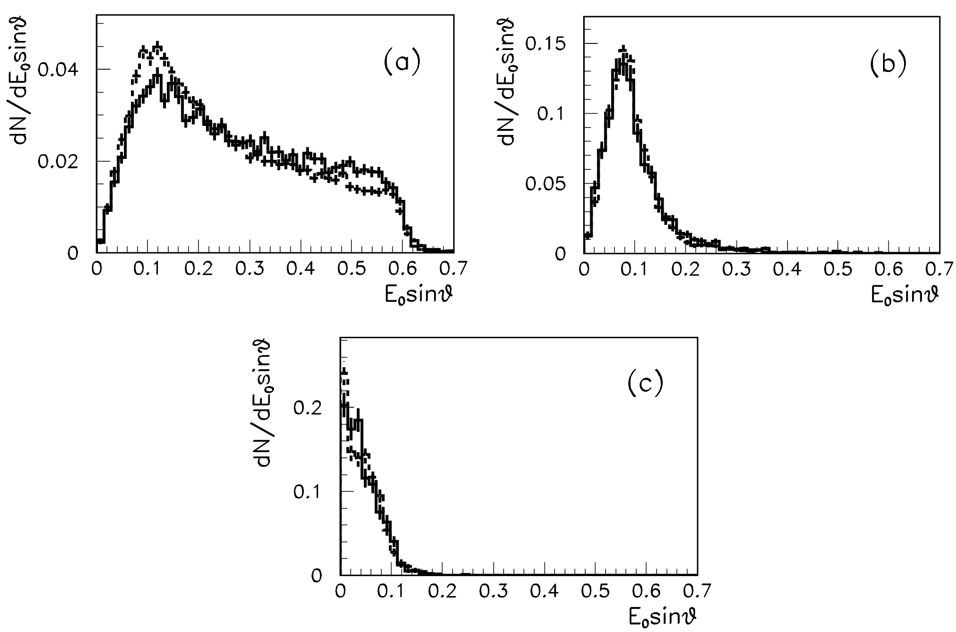

Fig. 7. Angular distributions of singly charged spectators (a), helium (b) and heavier fragments (c) in Pb+Pb (solid histograms) and Pb+PL (dotted histograms) interactions. The distributions are normalized to the same area.

In order to investigate whether the angular distributions of fragments, for a given energy transferred to the spectator part of the projectile nucleus, depend on the mass of the target we separate the analyzed interactions into two samples with different ranges of Z_b. In Fig. 8 we present the angular distributions of singly charged spectators, helium and heavier fragments in Pb+Pb and Pb+PL interactions with $Z_b \leq 40$ and $Z_b > 40$. We see that for $Z_b > 40$ the shapes of angular distributions for the same type of fragments do not depend on the mass of the target. For $Z_b \leq 40$ (more central interactions) the independence of the target mass is not so evident. This is especially perceptible for singly charged spectators.

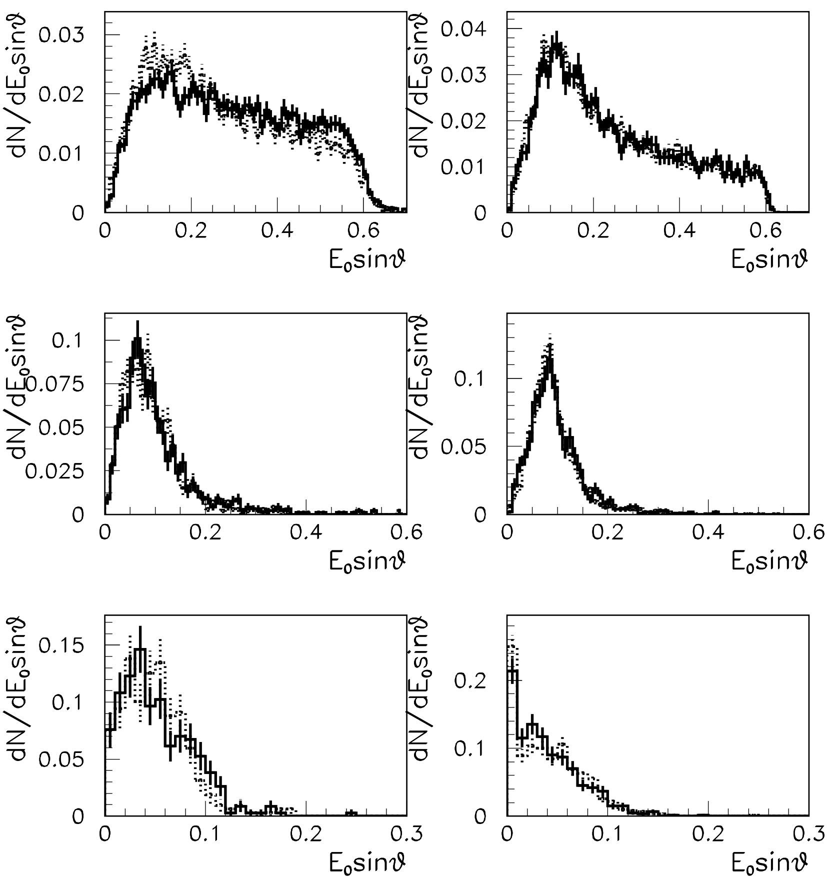

Fig. 8. Angular distributions of singly charged spectators (top panels), helium (middle panels) and heavier fragments (bottom panels) for Pb+Pb interactions (solid histograms) and Pb+PL (dotted histogram) interactions with $Z_b \leq 40$ (left panels) and $Z_b > 40$ (right panels).

6. Summary

Fragmentation of the projectile Pb nucleus at 158 A GeV after the collision with Pb or plastic ($C_5H_4O_2$) target has been investigated. We have found that at this high energy the electromagnetic interactions of Pb with Pb target play an important role. More than 50% of Pb+Pb collisions are due to electromagnetic interactions. They mainly contribute to events with the charge of the heaviest fragment not very different from the charge of the primary, however, there is still a considerable fraction of electromagnetic events among less peripheral interactions, which cannot be distinguished from the nuclear collisions.

The distributions of the number of fragments heavier than helium depend on the mass of the target, while their charge spectra do not. Also the shapes of the angular distributions of singly charged spectators, helium and heavier fragments are nearly independent of the mass of the target.

Using the sum Z_b of charges of multiply charged fragments as a measure of the energy transferred to the spectator part of the nucleus we observed that at a given Z_b the mean values of the number of singly charged spectators, helium and heavier fragments do not significantly depend on the target. Also, the mean values of charges of fragments are independent of the target mass, except for the most peripheral collisions, *i.e.* characterized by the largest Z_b values. Separating our experimental material into two samples of interactions with large ($Z_b \leq 40$) and small ($Z_b > 40$) values of energy transferred to the spectator nucleus, we found that for $Z_b > 40$ the shapes of angular distributions of the same type of fragments are the same, irrespectively of the mass of the target. For $Z_b \leq 40$ some differences in the shapes of angular distributions for light and heavy targets seem to be present, especially for singly charged fragments.

As it was already mentioned in Sec. 1 the process of nuclear fragmentation is a complex phenomenon that can be investigated in different ways. At present we put our attention on the general characteristics of nuclear fragmentation. In the future we will present the results of our analysis of charge correlations, moments of the charge distributions, critical exponents and some novel signatures to search for critical effects like *e.g.* the nuclear liquid-gas phase transition.

This work was partially supported by the Polish State Committee for Scientific Research (KBN) grant no. 2P03B05417.

REFERENCES

[1] M.L. Cherry *et al.*, *Acta Phys. Pol.* **B29**, 2155 (1998).

[2] A. Dąbrowska *et al.*, *Acta Phys. Pol.* **B32**, 3099 (2001).

[3] P. Deines-Jones *et al.*, *Phys. Rev.* **C53**, 3044 (1996).

[4] P. Deines-Jones *et al.*, *Phys. Rev.* **C62**, 14903 (2000).

[5] C.A. Bertulani, G. Baur, *Phys. Rep.* **163**, 299 (1988).

[6] H. Dekhissi *et al.*, *Nucl. Phys.* **A662**, 207 (2000).

[7] S. Cecchini *et al.*, DFUB 02/01, January 28, 2002.

[8] A. Schuttauf *et al.*, *Nucl. Phys.* **A607**, 457 (1996).

[9] A. Dąbrowska *et al.*, *Phys. Rev.* **D47**, 1751 (1993).

[10] A. Dąbrowska *et al.*, *Phys. Rev.* **C40**, 66 (1989).