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AN EVIDENCE FOR COLLECTIVE PHENOMENON IN HEAVY ION COLLISIONS AT 4.2 *A* GeV/c

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Recent data on $^{12}C + ^{12}C$ and $^{12}C + ^{181}Ta$ interactions at 4.2 A GeV/c from the 2 m JINR propane bubble chamber exposed at the Dubna Synchrophasotron are presented. The analysis of the flow angle distributions shows the «side-splash» effect in reactions with tantalum and carbon targets for high multiplicity events though for the latter case it is much less pronounced.

The investigation has been performed at the Particle Physics Laboratory and Laboratory of High Energies, JINR.

Наблюдение коллективных потоков в соударениях тяжелых ионов при 4.2 *A* ГэВ/с

А.П.Чеплаков и др.

Представлены данные по взаимодействиям $^{12}C + ^{12}C$ и $^{12}C + ^{181}Ta$ при 4.2 *A* ГэВ/с, полученные при облучении двухметровой пропановой пузырьковой камеры на синхрофазотроне ЛВЭ ОИЯИ. Анализ распределений по углу потока показывает наличие «side-splash» эффекта в соударениях с танталовой и углеродной мишенями в событиях с большой множественностью. В то же время эффект для углеродной мишени выражен менее заметно.

Работа выполнена в Лаборатории сверхвысоких энергий и Лаборатории высоких энергий ОИЯИ.

1. Introduction

High energy nucleus-nucleus interactions have been of growing interest in the recent years. This is mainly due to the fact that these collisions offer a unique opportunity to study properties of nuclear matter at extremely high densities and temperatures, where the phase

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transition of hadron gas to quark-gluon plasma and other novel phenomena may exist. In this context the main features of particle production and general properties of the intranuclear medium are to be studied covering both low and high energy regions in order not to miss a signal of exotics.

One of the most significant experimental results in this field was the observation of the collective flow of nuclear matter in the region of relatively low energies (around 1 GeV per nucleon) which was considered as the most important signature for the compression effects proposed by an equation of state. In the experiments with Plastic Ball [1] and later on with the streamer chamber [2] (both at the BEVALAC, Berkeley) the existence of the twofold collective effect was established: the «side-splash» of the participants and the «bounce-off» in the fragmentation region. Further investigations in the energy range around 1 GeV have confirmed the effect [3—5]. At higher energies (about a few GeV per nucleon) nuclei still exhibit a rather large stopping power [6], and so the collective flow might well exist in this energy region and its nature should be similar to that at low energies. However there was no experimental evidence for (or against) the stopping power [6], and so the collective flow might well exist in this energy region and its nature should be similar to that at low energies. However there was no experimental evidence for (or against) the existence of nucleonic collective flows at medium energies.

We searched for a possible manifestation of the nontrivial collective phenomena in collisions of carbon nuclei with carbon and tantalum ones at 4.2 GeV/c per nucleon. The experimental results are compared with the Monte-Carlo calculations according to the Dubna version of the cascade model (DCM) [7].

2. Experimental Details

The experiment was carried out with the 2 m propane bubble chamber exposed to the beams of d, ^4He and ^{12}C nuclei at the incident momentum of 4.2 GeV/c per nucleon from the Dubna Synchrophasotron. Three tantalum plates each 1 mm thick were placed inside the chamber volume. Events were recorded in the target plates as well as in propane. The statistics is ~2000 for $^{12}C + ^{181}Ta$ interactions and ~7000 for the $^{12}C + ^{12}C$ case. Protons were well separated from pions in the momentum range of $150 < p < 900$ MeV/c by ionization density. The contamination of misidentified π^+ mesons was about 8% of the number of fast positively charged particles with $p > 1$ GeV/c which were mainly fast protons [8]. The charges of fragments heavier than proton were determined by ionization density and also by means of counting δ electrons in the case of carbon exposure [9]. The contamination of such fragments was about 7% of the number pf positive tracks in the momentum range from 1 to 2 GeV/c [8]. The experimental setup and the data handling procedure are described in more detail in refs. [10—12].

For the analysis presented below we used the number of participant protons, i.e., protons which took part in the interaction, defined as

$$N_{\text{part}} = n_c - n_{\pi^-} - n_{\pi^+} - n_P^F - n_T^F, \tag{1}$$

where n_c is the number of charged particles in an event, $n_{\pi^-}(n_{\pi^+})$ is the number of $\pi^-(\pi^+)$ mesons and n_P^F (n_T^F) is the number of spectator fragments of the projectile nucleus (target nucleus). The value of n_T^F is determined by the number of spectator fragments of the projectile (or stripping particles) with $p/Z > 3$ GeV/c and with the emission angle $< 4°$. Protons with $p_{\mathrm{lab}} < 450$ MeV/c were considered as spectator fragments of the target the most part of which was absorbed by the tantalum plate. This boundary obtained in a special methodic analysis is rather nominal, however the charge of its absolute value within the limits of reasonable physical estimates does not affect the results of the experimental analysis presented below.

For the sake of proper comparison of the DCM predictions with the data, we have filtered the simulated events through the program which imitates the main features of the whole chain of the data taking and processing procedures. A good agreement of the inclusive single-particle spectra from simulated events with the data is a combined success of both the DCM and the filtering [8].

3. Event Shape Analysis and Collective Flow

Search for experimental evidence of collective effects in our experiment has been carried out by means of the events shape analysis based on the diagonalization of the kinetic energy flow tensor [13].

$$K_{ij} = \sum_{\nu} \frac{p_i(\nu)p_j(\nu)}{2m(\nu)} . \tag{2}$$

This sphericity tensor with the weight factor $1/2m(\nu)$ was determined and diagonalized for each individual event. For C + C collisions this procedure was performed in the center-of-mass system while for asymmetric C + Ta collisions we used two different reference frames as described below. In the event shape analysis we also used the flow angle, θ_{FL}, as a key variable. It is defined as the angle between the beam axis and the major axis of the flow ellipsoid obtained after the diagonalization of the K_{ij} tensor. In order to reveal the nontrivial collective nucleons flow (the «side-splash» effect), the θ_{FL} distributions for C + Ta and C + C collisions were obtained for different multiplicity selections, and the comparison with those calculated from the DCM was made.

The distributions of the flow angle θ_{FL} in the nucleon-nucleon center-of-mass system (NN c.s.s.) for all protons produced in C + Ta interactions at 4.2 GeV/c per nucleon for different intervals of multiplicity n_c are shown in Fig.1 (a). The corresponding distributions obtained from the DCM-simulated and appropriately filtered events are also presented on the right of this picture (Fig.1 (b)). As is seen from Fig.1 (a), the θ_{FL} distributions for all protons (spectators and participants) do not show any peculiarities at nonzero θ_{FL}, i.e., we do not see any «side-splash» of protons. Similarly the DCM also produces smooth distributions.

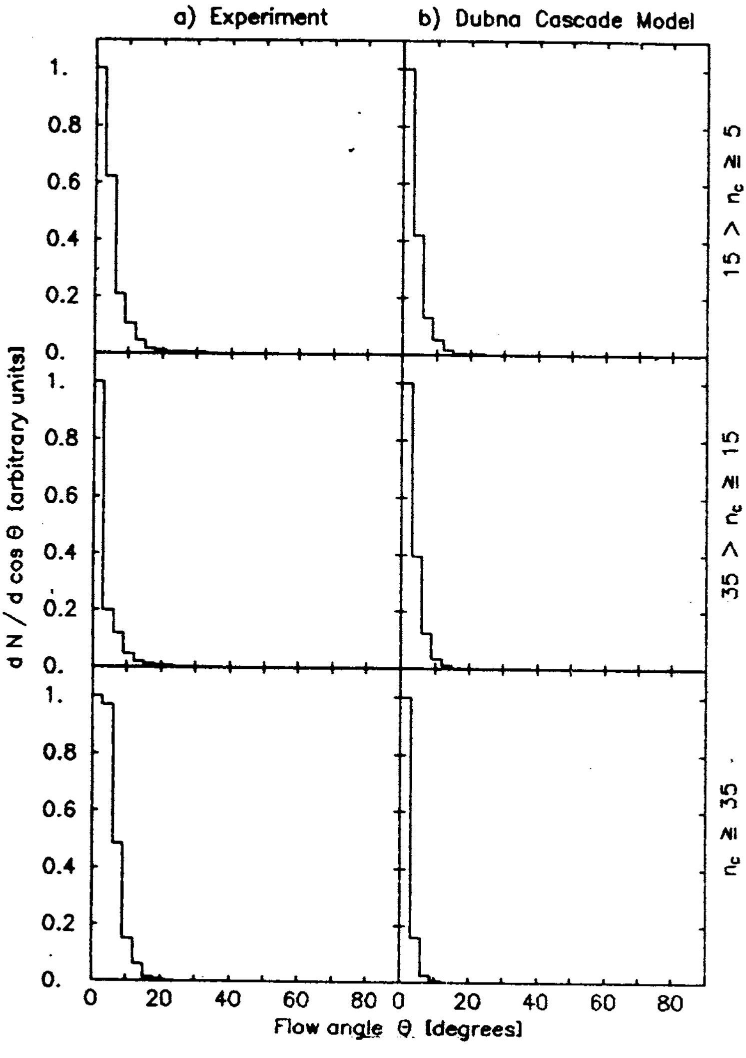

Fig.1. Flow angle distributions for C + Ta collisions in different multiplicity intervals for all protons in the NN c.m.s.

It should be noted here that as the data presented in Fig.1 (a) include also the spectators, the sidewards flow can be seen only if it is significant enough since the effect must be masked by spectator protons from the projectile which are mainly peaked at small angles ($\theta_{FL} < 10°$). This has been realized previously in the experiments at the BEVALAC [1,2]. Another point is that the NN c.m.s. is not quite meaningful when the masses of the colliding nuclei are not equal. Much closer to the proper c.m.s. of the interacting matter is the center-of-mass system of participant nucleons (p.c.m.s), in which $\sum p^*_{\text{long}}(\nu) = 0$, where ν

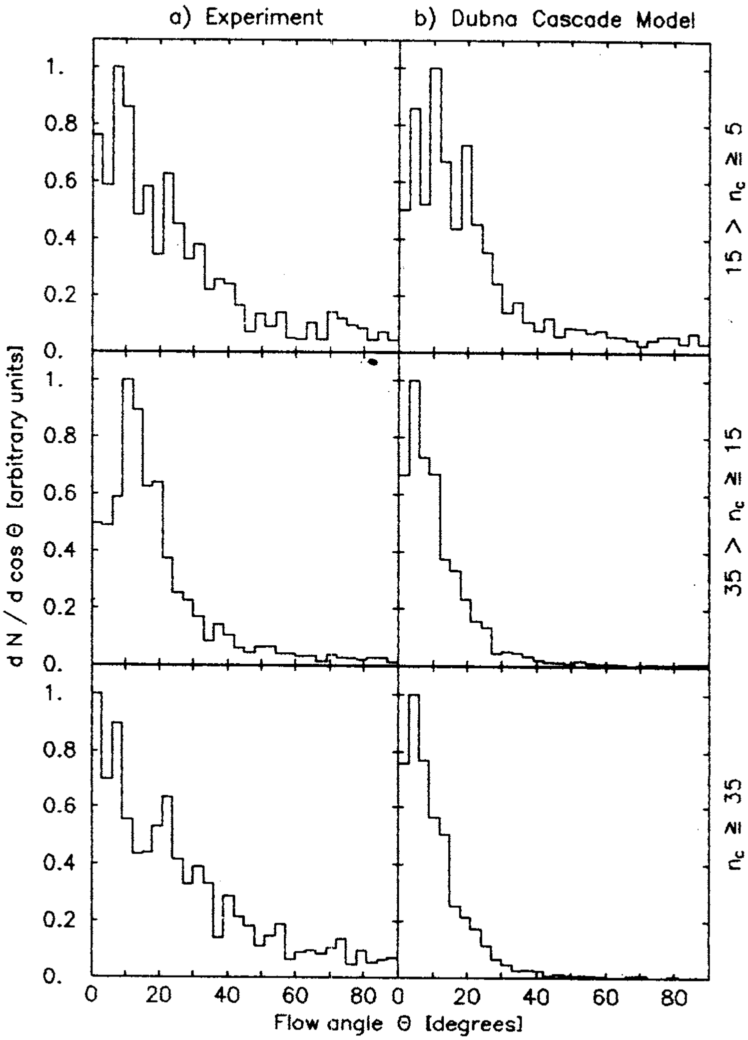

Fig.2. Flow angle distributions for C + Ta collisions in different multiplicity intervals for participant protons in their center-of-mass system

runs over the participant nucleons. Thus, in order to reveal a signal of collective «side-splash» (if any), we have also obtained the θ_{FL} distributions for participant protons in the p.c.m.s., i.e., in their own rest system. From the distributions presented in Fig.2 (a) it is seen that there is a distinct peak near $\theta_{FL} \sim 12°$ for the $15 \le n_c < 35$ charged multiplicity bin. The distributions obtained from the DCM, which does not comprise collective effects, are also shown in the same figure. These distributions demonstrate a rather smooth fall towards large θ_{FL} angles (Fig.2 (b)).

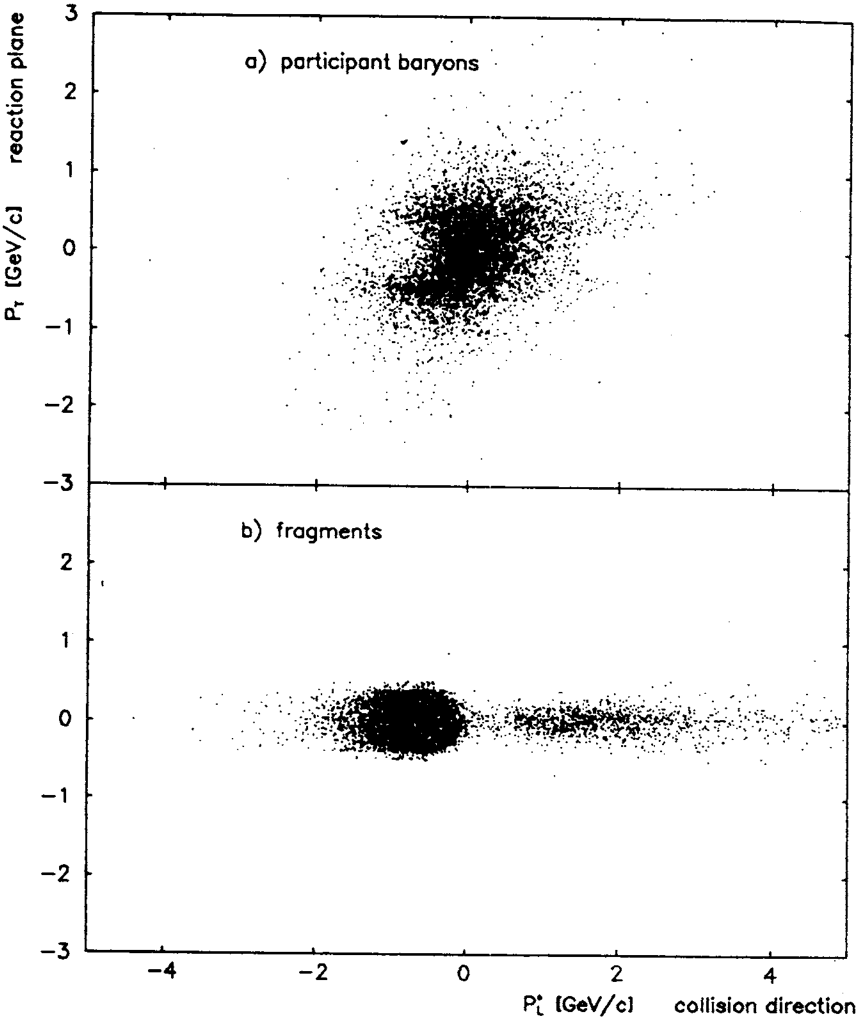

Fig.3. Projection onto the reaction plane of the momenta of participants (a) and spectators (b) in the c.m.s. of participants (C + Ta data, experiment)

Figure 3 presents an inclusive momentum configuration of participant protons and spectator protons of colliding nuclei for C + Ta interactions. For each event the longitudinal momenta of particles were Lorentz-transformed into the rest frame of participant protons. The plane containing the major axes of the K_{ij} tensor and the beam axis (reaction plane) was determined for each event and rotated by azimuthal angle φ in such a way that the individual reaction planes coincided with the $x-z$ plane, where the z-axis is the beam one. In other words, the reaction planes were superposed for all events. For better visualization only the particles having small momentum components transversal to the flow plane

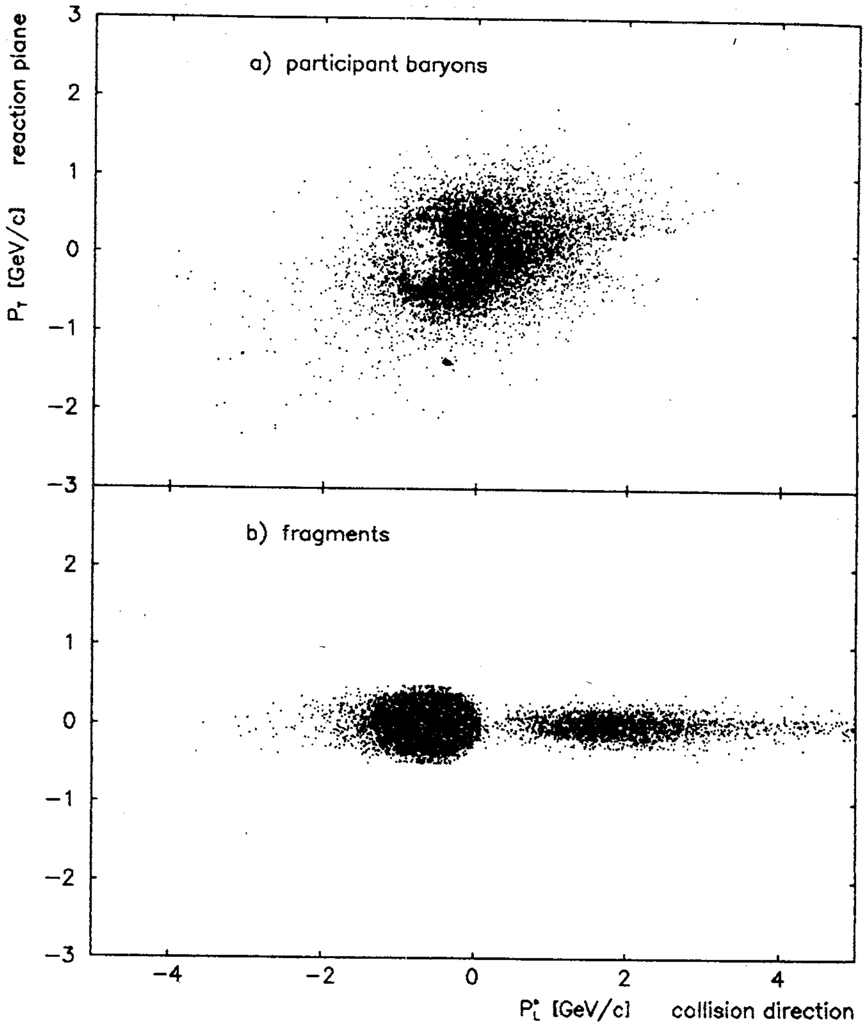

Fig.4. Projection onto the reaction plane of the momenta of participants (a) and spectators (b) in the c.m.s. of participants (C + Ta, DCM calculations)

($p_T^{out} < 0.2$ GeV/c) are shown. It is seen that our criteria for separation of the spectators work well since we do not observe any significant presence of nucleons from the fragmentation regions of colliding nuclei in Fig.3a. Analogous distributions from the cascade model are presented in Fig.4. The comparison of Figs.3 and 4 shows that the DCM describes qualitatively quite well the dynamics of collision at our energy. So, any significant deviation from the experiment can be considered as a possible signal of a collective phenomenon because there is no collective mechanism input in the DCM.

The above analysis shows that there is a finite deflection angle for a mid-multiplicity interval in C + Ta interactions. The same analysis was made for C + C interactions in our

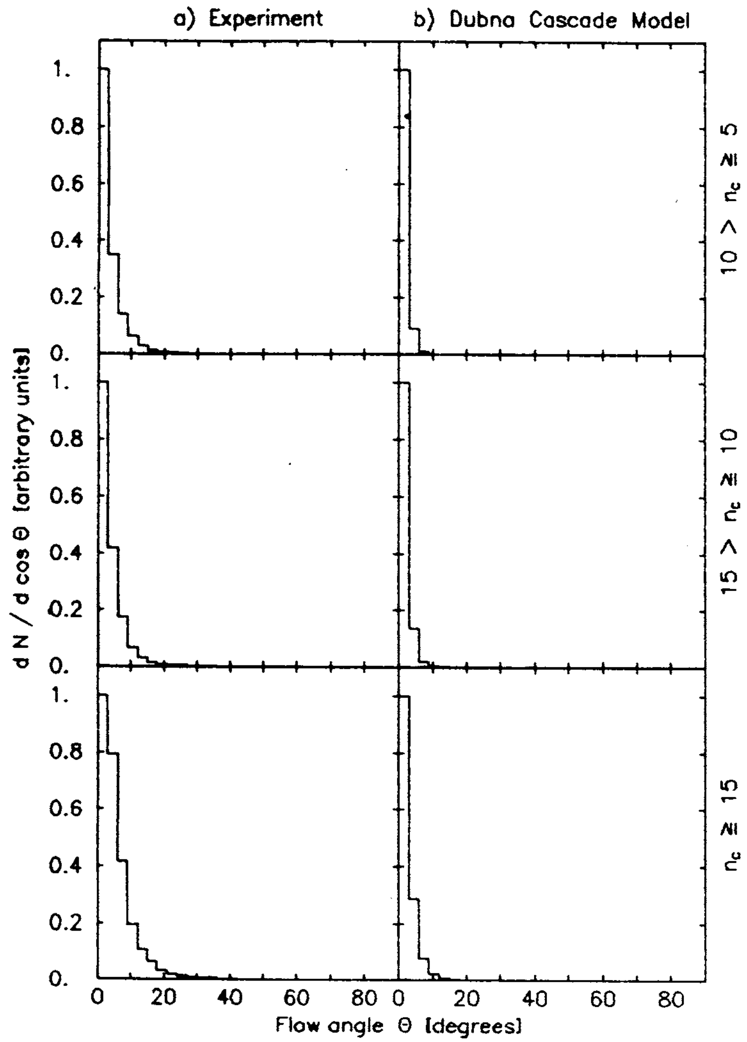

Fig.5. Flow angle distributions for C + C collisions in different multiplicity intervals for all protons in the c.m.s.

experiment. As in the case of C + Ta interactions, the θ_{FL} distributions of all protons in the c.m.s. of colliding nuclei were obtained for interactions of incoming carbon nucleus with carbon from propane (C + C interactions, Fig.5 (a)). Analogous θ_{FL} distributions of filtered events from DCM calculations are presented in the same figure (Fig.5 (b)). There is no structure seen in Figs.5 (a,b): the θ_{FL} distributions are smooth and fall down steeply. The flow angle distributions for C + C data, where only participant protons were included in the analysis, along with the DCM calculations are shown in Figs.6 (a,b). As is seen from Fig.6, the comparison of the experimental data with the cascade model calculations shows the

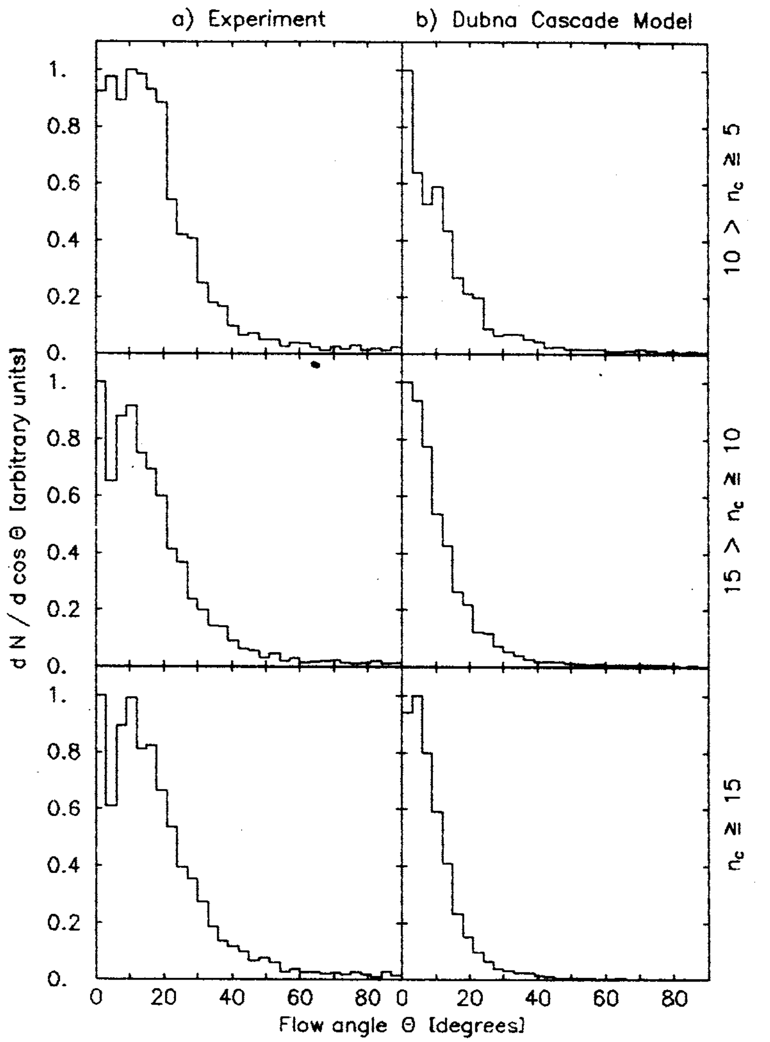

Fig.6. Flow angle distributions for C + C collisions in different multiplicity intervals for participant protons in the c.m.s.

presence of a nonzero peak for the experimental data in the last two intervals of multiplicity while the flow angle distributions for the DCM calculations are peaked at 0°.

Thus, the performed analysis allows us to draw a conclusion that there is experimental evidence of the collective flow of nucleons: the «side-splash» of participants in the collisions of carbon nuclei with tantalum and carbon. It is worth mentioning that in our experiment the flow angle distributions are peaked around 10°—12° for mid- and high multiplicity bins while in the experiments at the BEVALAC energies the finite deflection angle reached considerably larger values. This fact confirms the results obtained earlier at the BEVALAC where for different colliding heavy nuclei the decrease of the «side-splash» effect was observed with increasing energy [14].

4. Conclusion

Results from the global event shape analysis of the C + Ta and C + C data from the 2 m propane bubble chamber are presented. The investigation was made to search for collective motion of nucleons. For this purpose the flow angle distributions were analyzed. We compared the experimental results with the Dubna cascade model calculations. As the collective phenomena are not taken into account by this cascade model, it can serve as a good background for extracting collective effects from the experiment.

From the analysis of the experimental data it was deduced that the collective effect — «side-splash» of participants — is observed and is prominent for C + Ta data in a $15 < n_c < 35$ multiplicity interval. In C + C this effect is still observable for medium and high multiplicities but less pronounced. It is necessary to note here that the data presented above are the first experimental evidence of the collective effect of this kind in nucleus-nucleus collisions at energy essentially higher than 1 GeV/c per nucleon. The finite deflection angle increases with increasing multiplicity in our experiment as well as at the BEVALAC energies, but this dependence is different for symmetric (C + C) and asymmetric (C + Ta) collisions.

The comparison of the θ_{FL} distributions in our experiment with those obtained at the BEVALAC shows that finite deflection angle decreases with increasing energy. This fact is in line with previous experiments at Berkeley. Further investigations of the «side-splash» effect are required to understand the nature of this phenomenon better.

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