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The breakup of ^{16}O into He, an event by event study of nucleus-nucleus collisions at 75, 175 and 2000 A MeV.

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Abstract.

We present an event by event study of the breakup of the ^{16}O in ^{16}O+emulsion nucleus interactions at 75, 175 and 2000 A MeV. The events are cathegorized according to their multiplicity of projectile He nuclei. The multiplicity depends on the degree of target destruction. Although the fragmentation model describes the gross features of inclusive He-spectra, an event by event study reveals deviations from the model. The momenta of the He nuclei, emitted from the projectile, depend on helium multiplicity and the breakup properties of the target nucleus. The probability that the ^{16}O projectile breaks up into multiple He fragments is larger at 75 A MeV than at 2000 A MeV. At 75 A MeV the mean velocity of projectile He is on the average 0.06c below the projectile velocity. This recoil velocity depends on the target nucleus destruction also for the most peripheral collisions.

1. Introduction.

Helium emission in heavy ion reactions has been carefully studied from different aspects (1-7). In central collisions, angular distributions of He nuclei have played an important role in the search for shock-waves (1,2). In peripheral reactions the Goldhaber fragmentation (3,4), has satisfactorily explained the fragmentation of light projectiles, both into projectile-like fragments as well as into He nuclei. Experiments with heavy nuclei, show clear deviations from gaussian fragmentation, in different interaction channels (5-7).

In this investigation the inclusive He-spectrum is separated into its different constituents of events with 1,2,3 and 4 emitted He nuclei. Special attention is paid to angular and momentum distributions and the degree of target breakup. Data has been obtained at three different energies 50-100, 150-200 and 1900-2100 A MeV and studied with special emphasis on comparisons between the three energy intervals.

2. Experimental details.

In this experiment two stacks of nuclear emulsion (10 * 10 * 0.06 cm^3) have been exposed to the ^{1} O-beam at the Berkeley Bevalac, one at 250 A MeV (G5) and the other at 2100 A MeV (K2). Three volumes were selected for scanning, covering the energies 50-100 A MeV, 150-200 A MeV and 1900-2100 A MeV. In the following text, each energy interval is represented by 75, 175 and 2000 A MeV, respectively. Scanning efficiencies were tested by double and triple scanning and the maximum scanning losses were estimated to be < 5 % at 75 A MeV and smaller for the higher energies. The experimental material is summarized in table I.

TABLE I

Summary of the number of events and the mean energy in each energy interval.

E (A MeV)	<E>(A MeV)	number of events
50- 100	78	346
150- 200	177	487
1900-2100	2000	269

All tracks that could possibly be associated with the disintegrating projectile nucleus (i.e. within certain wide limits in emission-angle and range) were selected for further identification. Singly and multiply charged particles were easily separated by gap counting. Multiply charged fragments were then identified by photometric measurements (8). At 75 A MeV, all emitted He nuclei which do not interact, stop in the stack. The range is then measured and the energy determined. At 175 A MeV only about 50 % of all projectile He stop in the stack.

The emission angles of all multiply charged projectile fragments were determined by measurements of at least five coordinates on the projectile and fragment track, respectively. Thereby the accuracy in the angular measurement was $\pm$ 0.2 degrees.

In an emulsion experiment it is in general difficult to determine the identity of the target nucleus involved in the reaction. The percentages of reactions for different targets at 2000 A MeV (where reaction cross-sections are well-known) are: H (13%), CNO (29%) and AgBr (58%), for ^{16}O-induced reactions in emulsion. Recent experimental data at 86 A MeV (9), shows that the cross-sections are not very much different from relativistic data. Thus only a minor change in the target composition at 75 A MeV compared with relativistic energies can be expected.

The problem of deciding which particles originate from the projectile is essential for this type of event by event analysis and is worth a special discussion. Fig. 1 summarizes the effects, on the energy and rapidity (y) distributions from Goldhaber fragmentation at an incident energy of 75 A MeV. A simulation of the spectator fragmentation model was done by an independent generation of the momentum components P_x, P_y and P_z assuming gaussian shape of each component distribution, in the rest frame of the emitting nucleus. The momentum distribution was then transformed to the laboratory frame. We used the experimentally determined widths at 2.1 A GeV (4). The simulation was done for all He isotopes weighted together with the relative yields measured at 2.1 A GeV (10). The ^{3}He to ^{4}He ratio was 1/4. The distributions representing projectile fragmentation are broadened due to the spread of beam energies in the actual experiment. It is clear from fig. 1 that we should expect a separation between projectile and target fragmentation at 75 A MeV.

In the projectile fragmentation process at relativistic energies, the momentum of emitted He nuclei is on the average downshifted by ~ 30 MeV/c (0.008c) (4). However, at 75 A MeV the interaction time is considerably longer and therefore Coulomb effects may be of importance. Frictional forces might also reduce the momentum of the fragmenting nucleus. At intermediate energies, experimental evidence exist for an orbital deflection of the projectile prior to breakup (11). It has been observed at 75-100 A MeV, that singly and doubly charged particles are emitted from the projectile with a mean rapidity 0.06 below the projectile rapidity (12). A change of the momentum of the fragmenting nucleus with an added transverse momentum component of 25 A MeV/c and a parallel velocity shift of -0.06c, substantially shifts the distribution in fig. 1 (dashed curve). However, still a clear separation between projectile and target He particles is expected. This is very beneficial for a classification into projectile and target particles in peripheral reactions. The simplest criterion to use is to

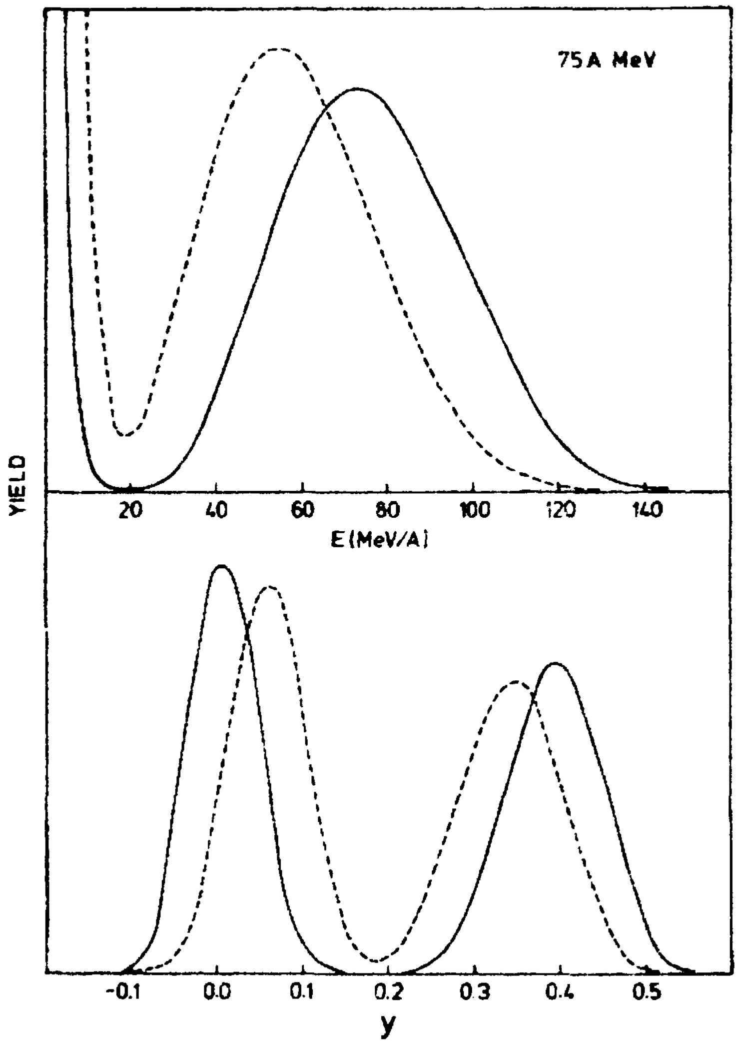

Fig. 1 Energy and rapidity distributions of He from a simulation of projectile and target fragmentation at 75 A MeV (solid), assuming equal projectile and target multiplicities. The dashed curve includes an added transverse as well as a parallel momentum component.

assume that all particles with $y > y_{beam}/2$ have been emitted from the projectile nucleus and all others originate from the target. This is of course an approximation, especially for singly charged particles. At 175 A MeV we observe events where only a fraction of the eight charges of the projectile is carried by particles with rapidity above $y_{beam}/2$. At 75 A MeV, protons from the projectile are frequently emitted with $y < y_{beam}/2$. However, our results are only affected when multiply charged fragments from the projectile are emitted below $y_{beam}/2$. Possible influences on the results are discussed together with the conclusions.

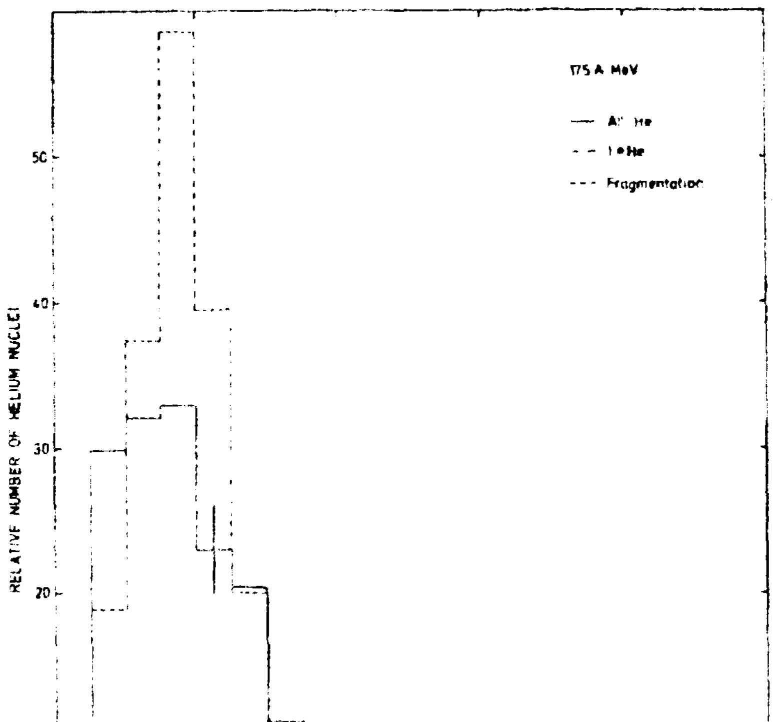

Fig. 2 Angular distribution of He particles at 175 A MeV (solid). The fragmentation simulation (dashed) is normalized to the total number of particles. The contribution from 1*He events is shown separately.

3. Angular distributions of projectile He.

Fig. 2 shows the angular distribution of He nuclei classified as projectile He at 175 A MeV (solid histogram). The dotted histogram exhibits the distribution expected from the projectile fragmentation. Compared with the calculated histogram, particles seem to be pushed, from the peak region towards larger as well as smaller angles. Similar deviations from the fragmentation picture have been observed at both intermediate and relativistic energies for He from ^{16}O (12,13).

In the next step we break this inclusive distribution down into different types of reaction channels. The different event types are as follows.

The ^{16}O-nucleus breaks up into:

a. 4 He nuclei (4*He)

b. 3 He nuclei + singly charged particles (3*He)

c. 1 He nucleus + $Z \geq 4$ fragment + eventually singly charged particles ($1*He+1*Z_{Fr} \geq 4$)

d. 2 He nuclei + singly charged particles (2*He)

e. 1 He nucleus + singly charged particles (1*He)

In table II the abundances of each reaction type are shown at the three energies.

TABLE II

The percentage of all reactions for each reaction channel.

	75 A MeV	175 A MeV	2000 A MeV
a	3±1	2±1	~ 1
b	11±2	12±2	10±2
c	12±2	9±2	3±2
d	17±2	17±2	10±2
e	10±2	12±2	15±2

A few comments to the table: there seems to be some energy-dependent effects e.g. the ^{16}O-nucleus is more likely to break up into multiple He fragments as the beam energy is decreasing. The contribution of He from 1*He events to all He is 9 ± 2 % at 75 A MeV, 12 ± 2 % at 175 A MeV and 20 ± 3 % at 2000 A MeV. This is an interesting observation, showing that the excitation of the non-overlapping spectator pieces of the interacting nuclei is not only ruled by the geometry in the collision. The geometry is almost identical at the three energies, why the observed differences in projectile breakup must indicate some kind of energy-dependent energy flow in the transverse direction to the outer parts of the interacting nuclei. Thus the excitation of the spectator is increasing when the beam energy grows. It should be argued that 1*He events are less peripheral than 4*He events. Experimental indications for this statement will be given later in the paper. The result implies that the clean-cut spectator-participant picture may work only for the very most peripheral reactions.

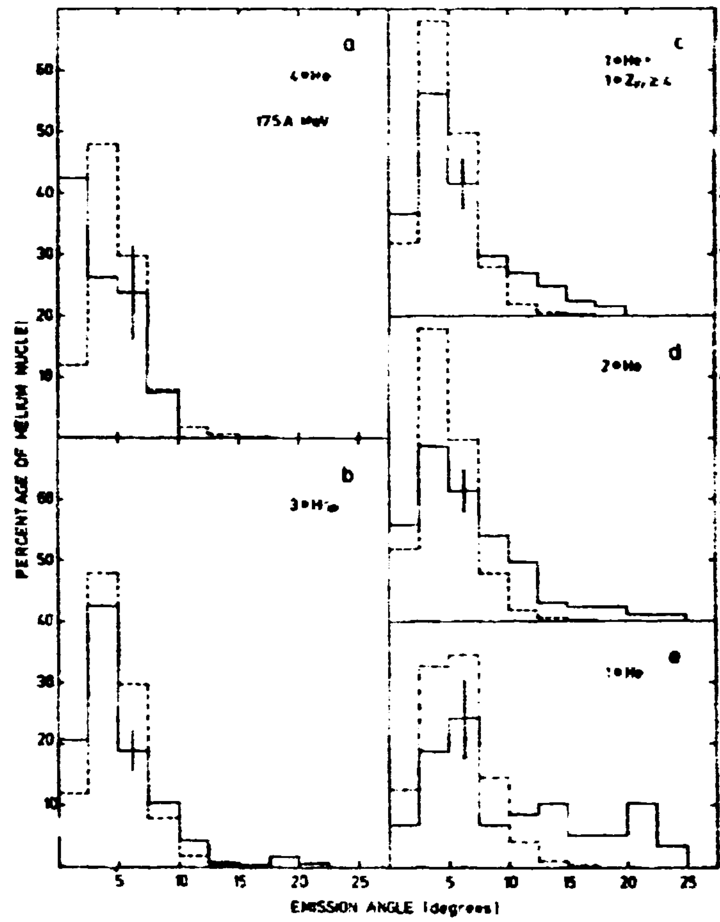

Fig. 3 Angular distributions of He in different reaction channels (solid). Dashed histograms show the fragmentation simulation, normalized to 100 % in each event cathegory. The simulation in panel e includes the strong parallel and transverse momentum shifts.

Regarding the angular distributions of projectile He nuclei in the different reaction channels at 175 A MeV in fig. 3, we notice significant differences. 4*He events have a very narrow angular spectrum, certainly narrower than expected from the fragmentation model. This is understandable if the fragmenting ^{16}O-nucleus, is regarded as a nucleus with an intranuclear substructure of four Helike clusters. The fragmentation model does not involve any such internal correlations between nucleons.

Angular distributions of 3*He and 1*He + 1*$Z_{Fr} \geq 4$ events exhibit the best agreement with fragmentation. There is, however, too few particles in the peak region and an enhanced large angle tail is noticeable. For 2*He and especially 1*He events the large angle tail is dominating and only a weak remnant of the fragmentation peak is seen. Similar observations are found both in the 75 and the 2000 A MeV samples. These results point at the difficulties in interpreting inclusive type of data. The additional information, gained in event by event studies, seems to be descisive enough to recognize deviations from fragmentation.

In fig. 4 the average emission angles in events with different He multiplicities and at different incident energies are compar.. with the predictions from the fragmentation model. We observe that the average emission angle depends on the He particle multiplicity at all three energies. 1*He and 2*He events show significant deviations from pure fragmentation. Coulomb effects might change the momentum of the projectile prior to breakup. Also other possibilities to produce a sidewards push of the projectile, e.g. the bounce off effect in the hydrodynamical picture (14), might be present. An additional transverse momentum of 25 A MeV/c together with a parallel retardation (0.06c) of the fragmenting cource is not enough to account for the 1*He and 2*He large emission angles.

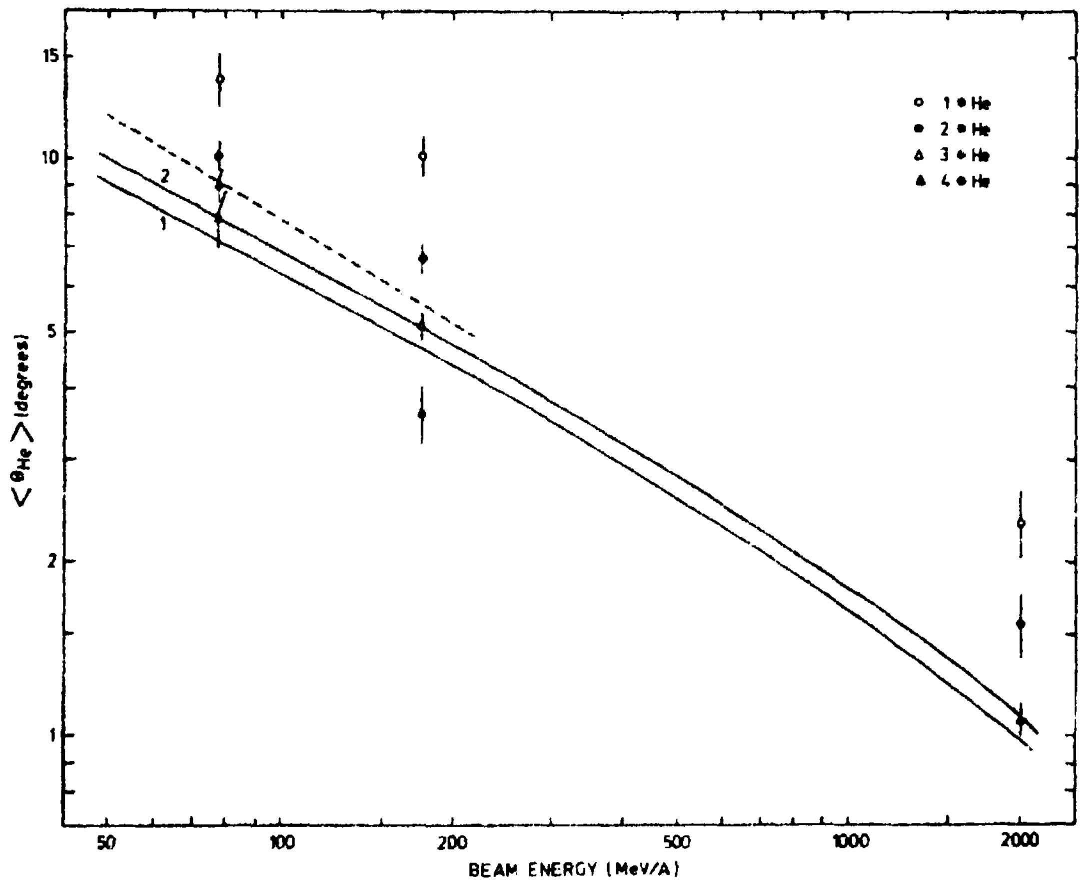

Fig. 4 The mean emission angle of He in different event types at 75,175 and 2000 A MeV. Curve 1 shows the fragmentation simulation. Curve 2 includes a transverse momentum component of 25 A MeV/c and the dashed curve also a strong retardation of 0.06c. At 2000 A MeV there is only one 4*He event. The average emission angle is 0.5 degrees.

4. Target breakup.

In this section, correlations between projectile and target breakup are presented. The number of charged particles emitted from the target nucleus, NT, is used to describe the degree of breakup of the target. NT is determined indirectly. By subtracting the number of charges tied up in multiply charged projectile fragments (the measured quantity) from the total charge of the projectile nucleus, i.e. 8, the number of singly charged particles from the disintegrating projectile is determined. The number of singly and multiply charged projectile particles is then subtracted from the total charged particle multiplicity in the event. There are possible effects that could make this procedure irrelevant e.g. the pickup of a projectile proton by the target (at 75 A MeV). Furthermore particles with y < 0.1 were always regarded as target particles. At 75 and 175 A MeV we neglect pion production. At 2000 A MeV, NT is close to NH (the number of heavy prongs). All identified low energy pions were however excluded.

Fig. 5 shows how the target particle multiplicity, <NT>, is correlated to the multiplicity of projectile He at different energies. There is a clear tendency that the target particle multiplicity is larger when the degree of breakup of the projectile is large. This could be understood as an impact parameter dependence in N*He (N is the number of He fragments). 4*He events are then very peripheral collisions while in 1*He events there are substantial pieces of the nuclei that overlap, which leads to a more violent disturbance of the interacting nuclei. For the most peripheral reactions, <NT> is independent of the beam energy over the wide energy interval from 75 to 2000 A MeV. A strong energy dependence is observed for

1*He and 2*He events. These collisions still have

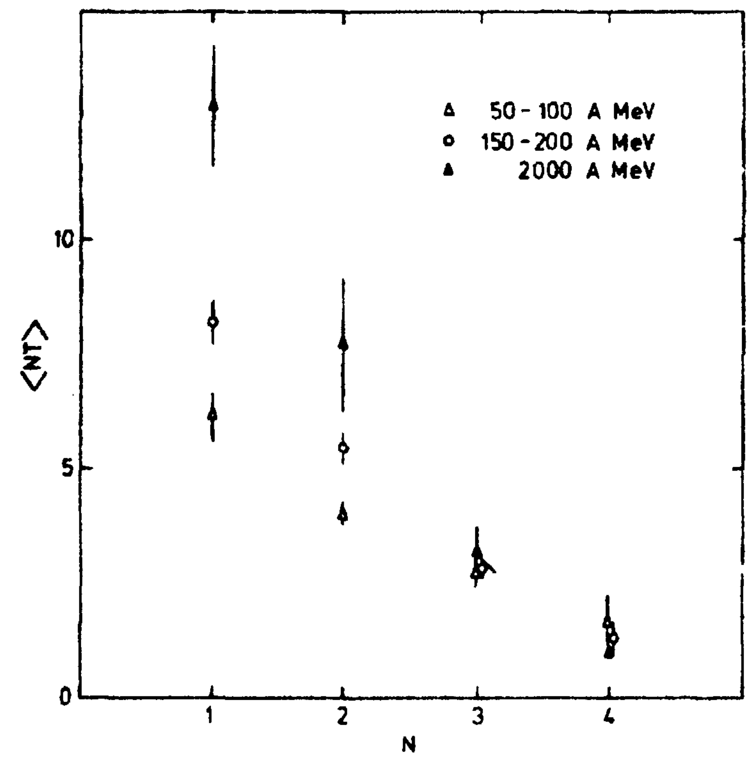

Fig. 5 The average number of target particles in each reaction channel at 75, 175 and 2000 A MeV. Events with 1*He + i*$Z_{Fr} \geq 4$ fit well among the most peripheral reactions.

large impact parameters. Events without any multiply charged projectile fragments have considerably larger <NT>-values. Most He nuclei we observe (also in 1*He events) are still too close to projectile momentum to have suffered a violent interaction with target nucleons. They are believed to originate from the non-overlapping projectile spectator.

Fig. 6 shows how the average emission angles of He nuclei depend on <NT>. There is a clear tendency that the emission angle is increasing when the target multiplicity grows. The fragmentation model predicts no correlation at all (dotted lines).

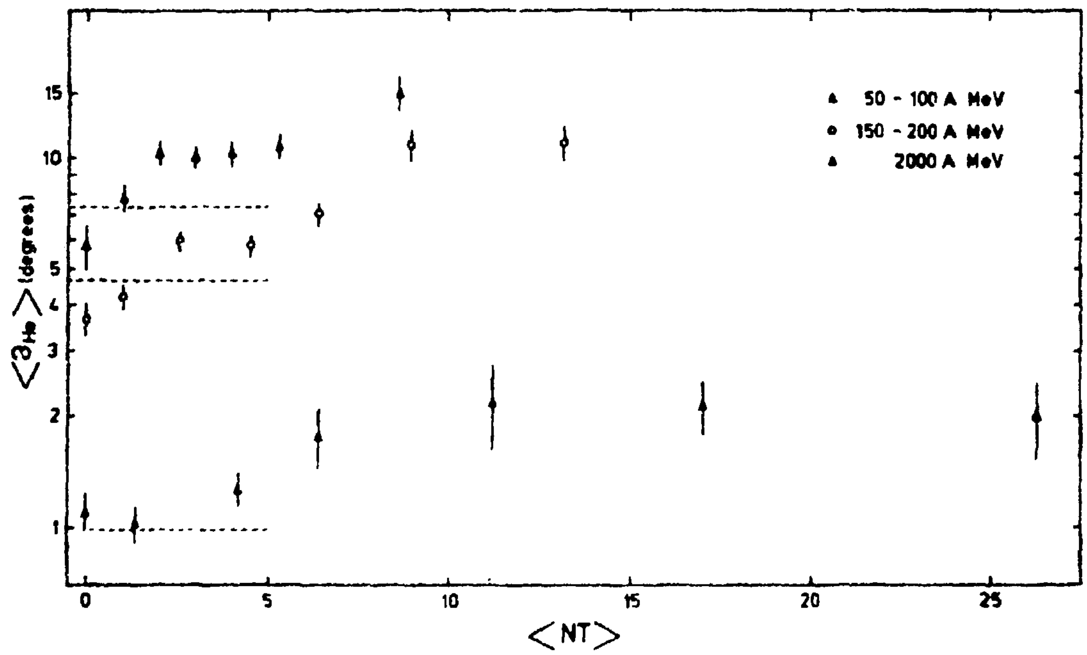

Fig. 6 The average emission angle for different bins of target multiplicity. The dotted lines represent the fragmentation prediction.

Figs. 5 and 6, which both explicitly show correlations between the projectile and target breakup properties, clearly tell that the excitation of the projectile and subsequent emission of He nuclei depend on what happens in the target. This contradicts the idea of factorization. Factorization means that the cross-section for a peripheral collision could be factorized in two parts: one, describing the breakup of the projectile, independently of the target disintegration and the other showing the target breakup, independently of the process in the projectile. Thus it does not seem to be possible to factorize the helium cross-section.

To further disentangle this phenomenon we present the correlations between the target multiplicity and the transverse momentum ($P_\perp$) and the rapidity of the emitted He particles. Since we have no isotopic separation, all He are assumed to be ^4He.

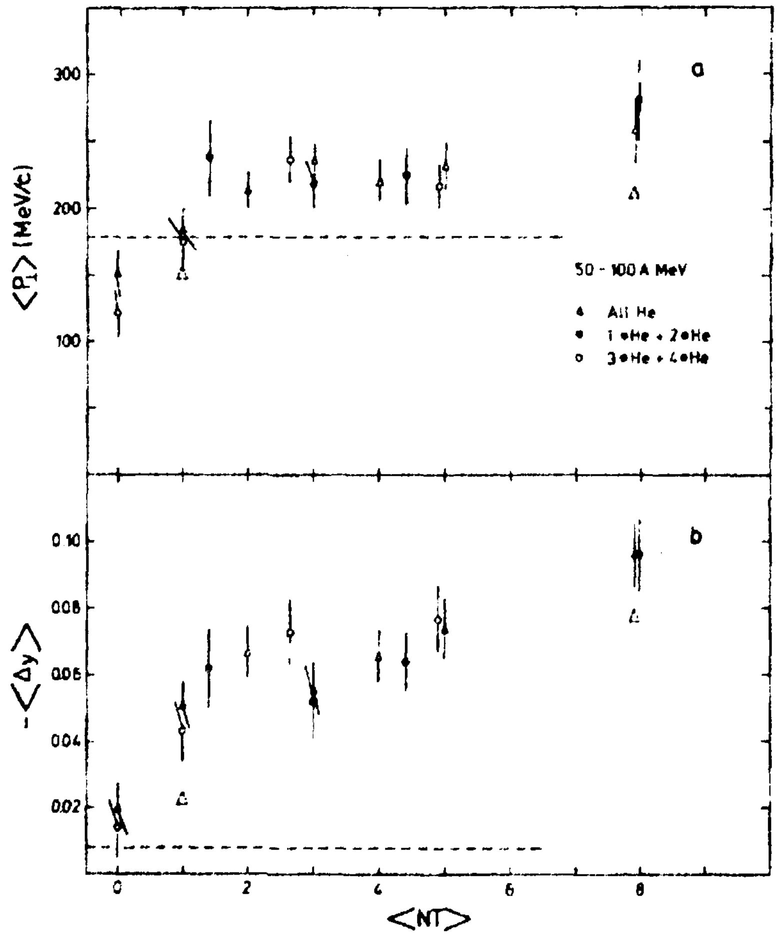

Fig. 7 The dependence of the mean transverse momentum (a) and the mean rapidity shift (b) on the target multiplicity at 75 A MeV. The dashed line represents the fragmentation calculation.

In fig. 7a the mean transverse momentum dependence on the target multiplicity is plotted. In collisions with a large breakup of the target, the projectile He are emitted with significantly larger transverse momenta than in events with small number of target particles. In the group of 3*He and 4*He there are events with as much as ~5 target particles. It is obvious that even in these most peripheral events, there is a correlation between transverse momentum and target multiplicity. Only for large <NT>, the transverse momenta are larger than expected from the fragmentation and independent of the disintegration of the target.

Fig. 7b examines the average shift in rapidity from the projectile rapidity for different <NT>-bins. The emitted He particles from the projectile are significantly downshifted in velocity compared with the projectile velocity. The average shift for the whole sample is 0.06c. The shift is much larger than the expectations from fragmentation of the projectile spectator. The shift is also dependent on the degree of target breakup and becomes stronger for large values of <NT>. Note that a correlation exists also in 3*He and 4*He events. The fact that some ^{3}He have been treated as ^{4}He in fig. 7 cannot alter the observed trends. The maximum error is illustrated with the dotted triangles which represent the $\langle P_\perp \rangle$ and $-\langle \Delta y \rangle$ values if all He were assumed to be ^{3}He.

5. Concluding remarks.

We have studied the topology of events where the ^{16}O projectile nuclei break up into one or more He nuclei. The collisions are typically large impact parameter collisions. The ^{16}O-nucleus breaks up more likely into multiple He fragments at 75 A MeV than at 2000 A MeV. The deposition of excitation energy in the spectator therefore seems to be energy dependent. The angular distribution of He in 4*He events is narrower than the distribution expected from projectile fragmentation. On the other hand, 1*He events have a too broad angular spectrum to be interpreted as the result of fragmentation. In 1*He events the projectile is interacting much more violently with the target nucleus than in 4*He events. The interaction mechanism is strongly energy dependent, resulting in a much larger target disintegration at 2000 A MeV than at 75 A MeV.

In 3*He and 4*He events the target multiplicity is independent of the beam energy. We observe correlations between target multiplicity, the number of projectile He and the emission angle of these He. Therefore, collisions where the ^{16}O-nucleus emits He nuclei cannot be factorized, not even in 3*He and 4*He events.

At 75 A MeV the He particles are significantly downshifted in rapidity compared to the projectile. The shift is strongest for large target multiplicity. This is observed also in 3*He and 4*He events.

Summarizing we find that, although the fragmentation model describes the gross features of inclusive spectra rather well, individual events exhibit details that contradict basic predictions of the model. We have illustrated the usefullness of doing event by event studies. Hopefully this type of investigations will have a break-through with the Plastic Ball experiments at LBL Berkeley.

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