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# Dominance of dissipative binary reactions in nearly symmetric nucleus-nucleus collisions above 35 MeV/u *

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***Abstract*** *: 4π detection of charged reaction products has been performed for the systems* $^{36}Ar+^{27}Al$ *at Elab = 55 - 95 MeV/u and* $^{64}Zn+^{nat}Ti$ *at Elab = 35 - 79 MeV/u. At all impact parameters, the velocity distributions of the charged products show mostly the de-excitation products of primary projectile-like and target-like nuclei. A single source, located at c.m. rapidity and due to fusion, is seen only in few violent collisions. Landau-Vlasov calculations reproduce the observed trends on both systems. These results demonstrate the vanishing of fusion and the dominance of dissipative binary reactions as early as 35 MeV/u in nearly symmetric systems.*

Nuclear reaction mechanisms at and above the Fermi energy have been the subject of numerous experimental and theoretical studies in the last decade. A transition from low energy reaction mechanisms dominated by mean field effects to novel de-excitation processes is expected at energies of several tens of MeV/u.

One of the first questions which arise is related to the number of nuclei, or nucleon systems, which are formed after the first step of the nucleus-nucleus encounter. In peripheral reactions, transfer reactions occur at all energies, with some projectile break-up at high energies. Usually, two main primary (projectile-like and target-like) nuclei are produced. In central collisions, the situation for all but heavy systems evolves from a very large cross section for complete fusion at low energy to a very small cross section for full stopping at high energies [1]. At these high energies, in almost the whole range of impact parameters, two excited "spectators" are left after emission of participant nucleons from the interaction region. At intermediate energies of 20 to 100 MeV/u, incomplete fusion or massive transfer mechanisms are invoked to explain the observed distributions of products, especially for heavy residues. The energies at which fusion dynamics are replaced by binary reaction dynamics remains an open question since most experimental data to date were obtained in inclusive measurements. Three sources of particles were observed : near the projectile rapidity, at small rapidity and at mid-rapidity. 4π multidetector arrays make it possible to detect most of the charged final products and to reconstruct the excited primary products on an event-by-event basis. In very asymmetric systems, the slow source was shown to be consistent with incomplete fusion between the heavy nucleus and part of the light one. In symmetric or nearly symmetric systems, the situation is not clear. For very heavy systems, fusion does not occur at energies below 20 MeV/u, even in central collisions. For $^{129}Xe+^{nat}Ag$, $^{197}Au$ collisions at 23.7 and 27 MeV/u, the overall trends of inclusive data can be explained by binary processes (modified participant-spectator model or extended deep inelastic model) [2]. 4π measurements performed for the heavy systems $^{209}Bi+^{136}Xe$ [3] and Pb+Au [4] indicate that the binary character persists at 28-29 MeV/u for the most dissipative (central) collisions. For systems which undergo fusion below 10 MeV/u, indications of a binary behavior for Ar+Ag collisions were found [5], but binary behavior was not needed to explain data obtained in another study of the same system [19]. We present in this paper evidence of a binary behavior at the level of ~95 % of the reaction cross section in a rather light system, $^{36}$Ar on $^{27}$Al from 55 to 95 MeV/u, and a medium mass system, $^{64}$Zn on $^{nat}$Ti, from 35 to 79 MeV/u. These systems are nearly symmetric with the same entrance channel mass ratio of 1.3. In the analysis of a previous experiment, $^{40}$Ar+$^{27}$Al from 36 to 65 MeV/u, it was assumed that incomplete fusion occurred in central collisions [6] ; the possible binary nature of the reaction was not addressed and these data have been reanalyzed.

The disappearance of evaporation residues in the Ar+Al system at 19.7 MeV/u was interpreted to be due to the sequential decay of the compound nuclei rather than to the vanishing of fusion-like products [7]. Ref. 8 showed that composite nucleus formation vanishes above 27 MeV/u, which was tentatively attributed to a temperature limit of the composite nucleus. At 44 and 60 MeV/u, the correlation between the projectile-like and the target-like fragments formed in peripheral interactions was measured and explained by an extended version of the abrasion-ablation model or by equal excitation energy sharing between the two nuclei [9]. For systems close to Zn+Ti, peripheral collisions have been studied in $^{40}$Ar+$^{68}$Zn reactions at 27.6 MeV/u [10]. Residues attributed to incomplete fusion have been detected in $^{40}$Ar on $^{45}$Sc collisions at 27.5 MeV/u [11].

The experiments were performed at the Ganil facility in the reaction chamber Nautilus. Charged products were detected in a nearly $4\pi$ geometry using two complementary multidetector systems MUR [12] and TONNEAU [13]. The forward angles between 3.2° and 30° were covered by a wall of 96 plastic scintillators arranged in 7 concentric rings located 210 cm from the target. Angles between 30° and 150° were covered by a spherical barrel which was located 80 cm from the target. Seven large solid angle silicon telescopes installed 60 cm from the target covered polar angles from 3° to 30°.

A minimum bias trigger was used in which all events with a multiplicity larger than one were recorded. In the MUR and TONNEAU the velocities of particles and fragments were measured and the corresponding charges identified up to Z = 8 using the energy-loss versus time-of-flight technique (up to Z = 3 for particles stopping in the scintillator). In the telescopes, kinetic energies and charges were derived from a $\Delta$E-E measurement. The masses of the fragments were obtained from their charges. Since a kinematic analysis relies on velocity, the Si telescopes were accurately calibrated by means of fragments with Z ranging from 1 to 10 and velocities selected by a high resolution magnetic spectrometer in a separate measurement. The telescopes identified Z up to 30.

The first step in the analysis was to ensure that sufficient information had been obtained on the event to be analyzed. We used the sum of the momenta of all detected particles to determine the completeness of the events. A distribution of this parameter shows two peaks ; one around 20 % of the projectile momentum contains approximately 25 % of events and the other located around 80 % of the projectile momentum. All events that we analyzed were in the upper peak [14]. Since the grazing angle is smaller than the minimum detection angle of 3.2°, most eliminated events were peripheral reaction events, because the projectile-like fragment was generally not kicked to more than 3.2° and most of the linear momentum was not measured. This means that all central and intermediate impact parameters were analyzed as well as most of the semi-peripheral impact parameters and a few peripheral reactions i.e. ~75% of the reaction cross section. Their measured charge was around 75 % of the total charge of the system.

The next step was to sort the events as a function of the violence of the collision. The total transverse momentum $P_\perp$ ($\sum_i |p_t^i|$ where $p_t^i$ is the transverse momentum of fragment i has been used to estimate the impact parameter $b_{exp}$ [14]. It is strongly related to the amount of energy transformed from relative motion into other degrees of freedom.

The first indication about the character of the collisions is the number of sources. There are always mid-rapidity particles emitted from the interaction zone (pre-equilibrium particles or participants). If the reaction remains binary, two other sources (a fast one and a slow one) of reaction products should be observed. If fusion occurs, one should observe one source at c.m. rapidity (undistinguishable from the mid-rapidity source).

In order to see the sources at each impact parameter bin, the Lorentz invariant cross section map $d^2\sigma/p_t^i dp_t^i dy$ was plotted for different products. Figure 1 shows the data for Zn+Ti collisions at 57 MeV/u. Similar maps have been published for $^{40}$Ar on $^{27}$Al [6]. For Z = 1 and 2 particles, two sources are seen at all impact parameters. The velocity of the fast source is close to the projectile velocity in peripheral collisions and decreases with the impact parameter. In the most violent collisions, a large dissipation occurs since the velocity of the fast source is only ~75% of the projectile velocity. However, it remains well above $\beta$cm. The velocity of the slow source is small but its value cannot be determined since it is well below the detection threshold. A third source is located at mid-rapidity. It can hardly be seen in Fig. 1, but appears clearly in the average value of transverse momenta versus rapidity [20]. For heavier fragments, the mid-rapidity contribution vanishes, the larger detection threshold suppresses many slow products and only the fast source is visible. It has the same location as Z = 1 and 2 particles.

Additional information on the binary behavior can be obtained by reconstructing the charge (or mass) of the primary nuclei which constitute the slow and fast sources. The detection threshold prevents the reconstruction of the primary nucleus for the slow source, but all products from the fast source are above the thresholds. Since the MUR and TONNEAU do not identify the charges above 8, an additional selection was to take those events in which the heaviest product (residue) is detected in a telescope, thus ensuring the measurement of the events is as complete as possible. Indeed, in peripheral collisions, only light particles accompany the heavy projectile-like residue and in all but very few central collisions the system splits into many products with a charge $\leq 8$ .

The velocity vector of the fast quasi-projectile source was reconstructed for each event from the momentum vectors of the products with rapidity Y greater than Ycm, as indicated in fig. 1. A variation of ± 10 % on the value of this cut was found to have a negligible effect on the results since it mostly affects light particles. The nearly isotropic decay of these nuclei is clearly seen in the reference frame of the primary nucleus [15]. Indeed, the c.m. angular distributions of Z = 1, Z = 2 and IMF's ($3 \leq Z \leq 8$) exhibit a flat behavior in the forward hemisphere. According to calculations made in the framework of the Landau-Vlasov equation, the distribution of pre-equilibrium nucleons extends up to large rapidities. Therefore, they mix with the products emitted by the fast source, especially in central collisions. This contamination is weaker at forward angles. Therefore, the charge of the primary nucleus is determined by taking the products emitted in the forward hemisphere in the reference frame of the primary nucleus. A correction is made for the geometrical efficiency of the detector array, and a factor 2 is applied in order to get the contribution over $4\pi$ [6]. The charge of the primary nucleus thus obtained is multiplied by the system mass-to-charge ratio to get the mass. Since some pre-equilibrium contamination remains, the value so obtained is overestimated, especially in central collisions.

The average mass of this primary nucleus is plotted in fig. 2 as a function of the estimated impact parameter $b_{exp}$ deduced from $P_{\perp}$ for both systems at all incident energies. The striking fact is that this overestimated mass remains below the projectile mass at most impact parameters. This is at variance with fusion and in agreement with a process where the initial nuclei keep their individuality : nucleon-nucleon collisions in the interaction zone lead to the emission of some fast nucleons and clusters (preequilibrium mid-rapidity source) ; the other ones are stopped in the quasi-projectile and quasi-target nuclei which are thus excited. Some part of the dissipated energy might be in the form of compression. The excitation and compression energies of the primary quasi-projectile nucleus will be studied in another paper.

In fig. 2, the average residual mass of the fast source is also shown. It decreases with the impact parameter. The lower the impact parameter, the larger the mass lost by the primary nucleus, which means the larger the excitation energy deposited in the primary nucleus.

The variation of the average residual mass with $b_{exp}$ is evidence that the impact parameter sorting is effective in separating different classes of events. In central collisions, it is between 1/3 and 1/4 of the primary mass.

A comparison to a Landau-Vlasov code [16] using a momentum dependent Gogny D1-G1 force is shown in figures 1 and 2. The bottom panel of figure 1 can be compared with the Zn+Ti experimental data for $Z = 1$ and 2. The mid-rapidity, fast (projectile-like) and slow (target-like) sources are seen in central collisions having $b < 2$ fm as well as in peripheral collisions having $b = 6$ fm at 62 MeV/u. The mid-rapidity source is observed to be stronger than in the experiment. In fig. 2, the closed triangles show the mass of the fast source when it separates from the target-like source, after a time of around 70-90 fm/c, depending on b. At 6 fm, it is equal to the experimentally reconstructed mass but is lower at 2 fm. The calculated angular distribution of emitted particles after separation is isotropic in the fast source frame. Part of the emission prior to separation is also isotropic in this frame. It explains why the experimental mass, based on isotropy in the forward $2\pi$, is larger than the calculated mass at separation. Experimentally, the mass at separation cannot be determined, except that it is intermediate between the reconstructed mass and the residual mass. Closed circles show the calculated residual masses at a large time (800 fm/c), in good agreement with the measured masses. For Ar+Al, calculations have been made at several impact parameters (fig. 2 top). The conclusions are the same as for Zn+Ti.

Are there events with a single source, i.e. (incomplete) fusion events, in central collisions ? Data obtained for Ar+Al at 55 and 86 MeV/u are presented in fig. 3. Quite similar data were obtained at other energies (67, 79 and 95 MeV/u) and for Zn+Ti at all energies. The upper row at each energy corresponds to $b_{exp}$ estimated to be < 1 fm. Among these events, we have searched for those having a single source close to c.m. Since $Z \geq 7$ fragments are observed only at large rapidities, the corresponding events were removed. The high and low rapidity parts of $Z = 1$ and $Z = 2$ plots decreased just a bit. An additional selection of central (violent) collisions by another global variable was needed. We tried keeping only the higher half of the multiplicity distribution. This had a weak effect . The requirement of $b_{exp} < 1$ fm given by the average parallel velocity [14], chosen because it is almost uncorrelated with $P_\perp$, also had a very weak effect. The transverse momentum directivity $D = \left\| \left| \sum_i \vec{p}_t^{\,i} \right| / \sum_i \left| \vec{p}_t^{\,i} \right| \right\|$ is low in very central collisions since there is no preferred azimuthal direction [1]. D was calculated separately for Yi > Ycm and Yi < Ycm since the detector thresholds affect only Yi < Ycm. Both D distributions have a maximum around 0.3 (0.4 in fig. 2, ref. 1) and their correlation is weak. Selecting events with both D values below 0.2 lead to a reduction of the fast and slow sources. A better selectivity has been obtained with the ratio of the total transverse energy to the total c.m. longitudinal energy $E_\perp / E_{//}$ [17]. This ratio is similar to the isotropy ratio [18]. For two sources located away from Ycm, this ratio has a low value. When the distribution of particles becomes more compact around Ycm, its value increases. It is close to 2, on the average, in the limit of an isotropically decaying source located at Ycm. We have taken a less stringent requirement, i.e. $E_{\perp} / E_{//} > 1.5$. Then, one obtains the lower row at each energy in fig. 3 where the fast and slow sources are strongly reduced, especially at the lower incident energies ; most events in the lower rows belong to a different class of events than the main portion in the upper rows.

Since events in both rows have the same measured total parallel momentum and total charge distributions, these events cannot simply be less well characterized events just satisfying by chance the selection criteria. There are some such fusion events at $b_{exp}$ values up to 3 fm and the upper limit of the fusion cross section is 50 mb at the lowest incident energies and decreases at higher energies. This figure can be compared to the geometrical overlap cross section which is ≤ 30 mb, since full overlap occurs below 1 fm for these nearly symmetric systems. When comparing these data with other experimental data or simulations, one should take care of the cross section numerical values. There are usually events which can be attributed to incomplete fusion, the point is to determine their cross section.

In conclusion, binary collision dynamics dominates above 35 MeV/u in the nearly symmetric systems $^{36}Ar+^{27}Al$ (or $^{40}Ar+^{27}Al$) and $^{64}Zn+^{nat}Ti$. This dominance is observed at all degrees of dissipation. Fusion is observed in central collisions with a cross section not exceeding a few percents of the reaction cross section. The transition from dominating fusion to dominating dissipative binary collisions occurs at incident energies around 35 MeV/u for nearly symmetric light and medium-mass systems.

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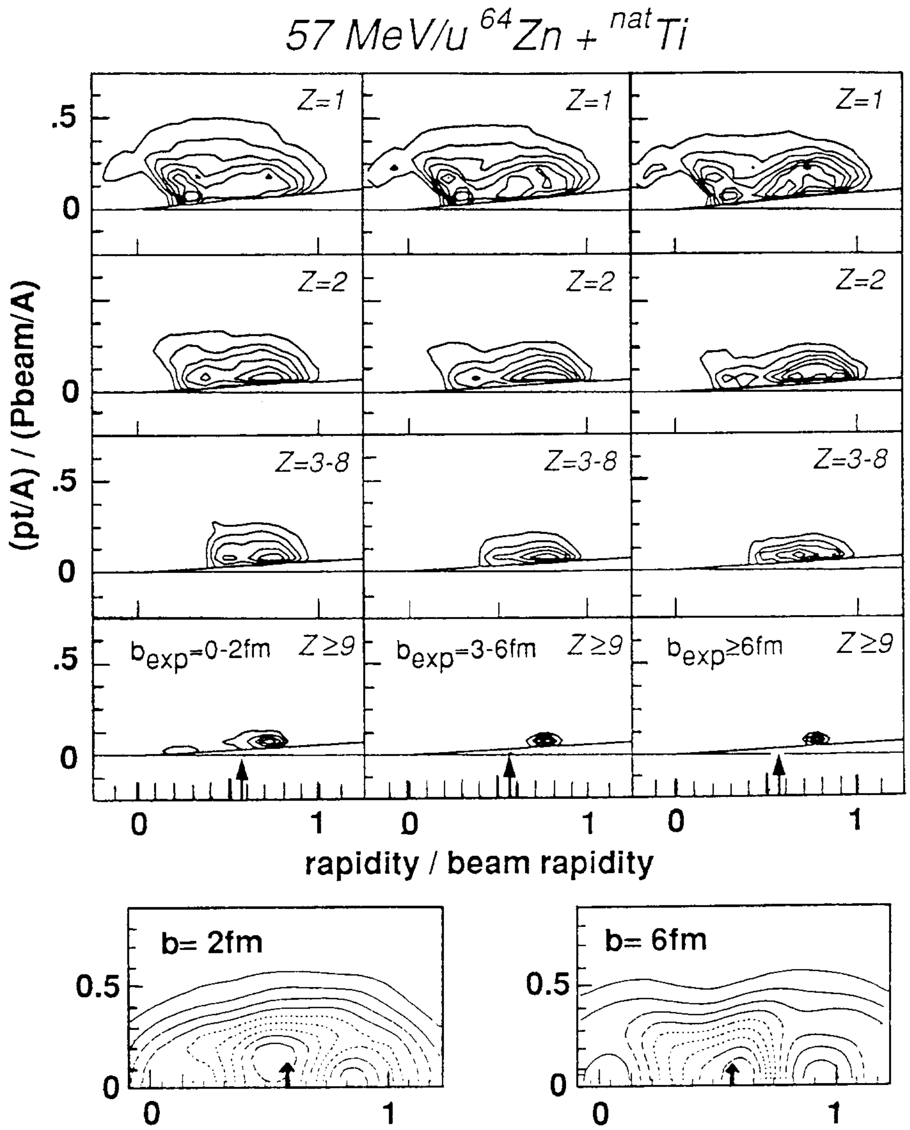
Fig. 1 : Invariant cross section $d^2\sigma / dy\, dE\, dP_\perp$ for Z = 1, 2, 3-8 and ≥ 9 fragments in 3 estimated impact parameter bins. The abcissa is the laboratory rapidity normalized to the projectile rapidity and the ordinate is the transverse momentum per nucleon relative to the projectile momentum per nucleon. The arrows indicate the c.m. rapidity (relative to the projectile rapidity). Top : experimental data (Zn+Ti at 57 MeV/n) for Z = 1, 2, 3-8 and ≥ 9 respectively, in three impact parameter bins. Bottom : Landau-Vlasov calculations of emitted nucleons for 62 MeV/u Zn+Ti at 2 and 6 fm.

Fig. 2 : Experimental data and Landau-Vlasov calculations for $^{36}Ar$ + $^{27}Al$ (top) and $^{64}Zn$ + Ti (bottom) systems as a function of the impact parameter. The experimental data are shown by open symbols. In each figure, the lower points show the average residual mass of the fast source, the upper points show the average reconstructed mass of the fast source (projectile 'spectator'). The reconstructed mass includes some pre-equilibrium contribution, especially in central collisions. The horizontal bars show the estimated impact parameter bins. The vertical bars in Zn+Ti show the variances of the distributions. Landau-Vlasov calculation results at 65 MeV/u for Ar+Al and 62 MeV/u for Zn+Ti are shown by closed symbols. Points : average residual mass of the fast source ; triangles : average mass of the fast source at the moment of separation.

Fig. 3 : Experimental data of $^{36}Ar$ on $^{27}Al$ reactions : contour plots for Z = 1, 2, 3-6 and ≥ 7 at 55 (top) and 86 MeV/u (bottom). At each energy, the upper row contains all events with an estimated impact parameter ≤ 1 fm, the lower row contains the events of the upper row which have a large $E_\perp / E_{//}$ ratio (fusion , see text). Same abcissa and ordinate as in fig. 1.

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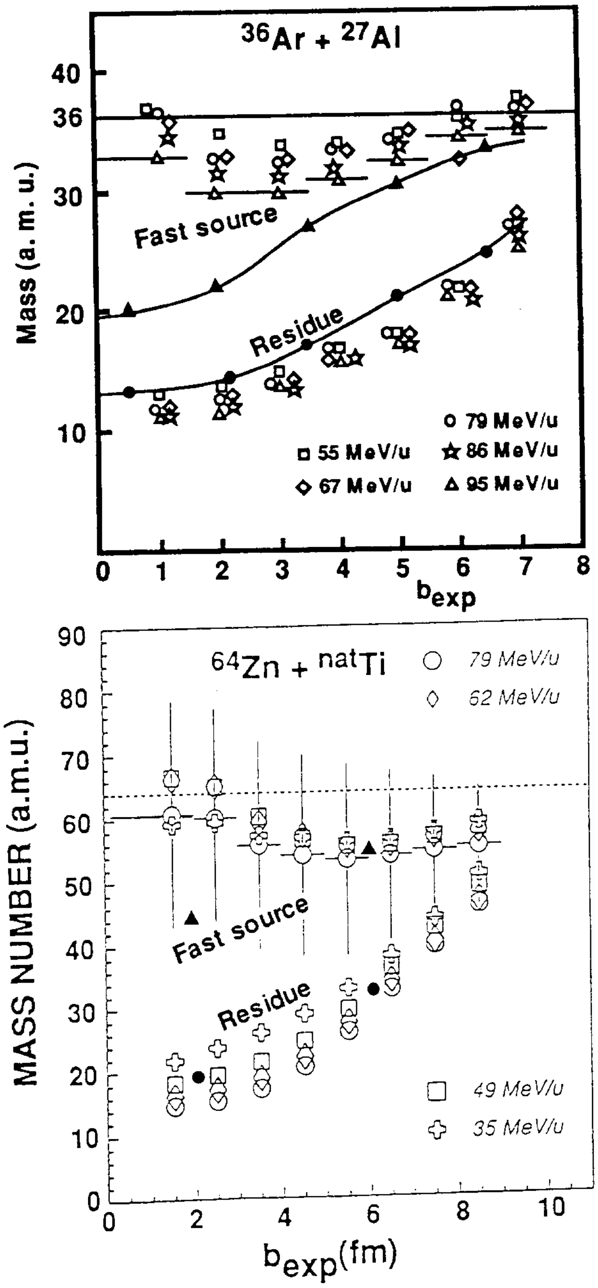


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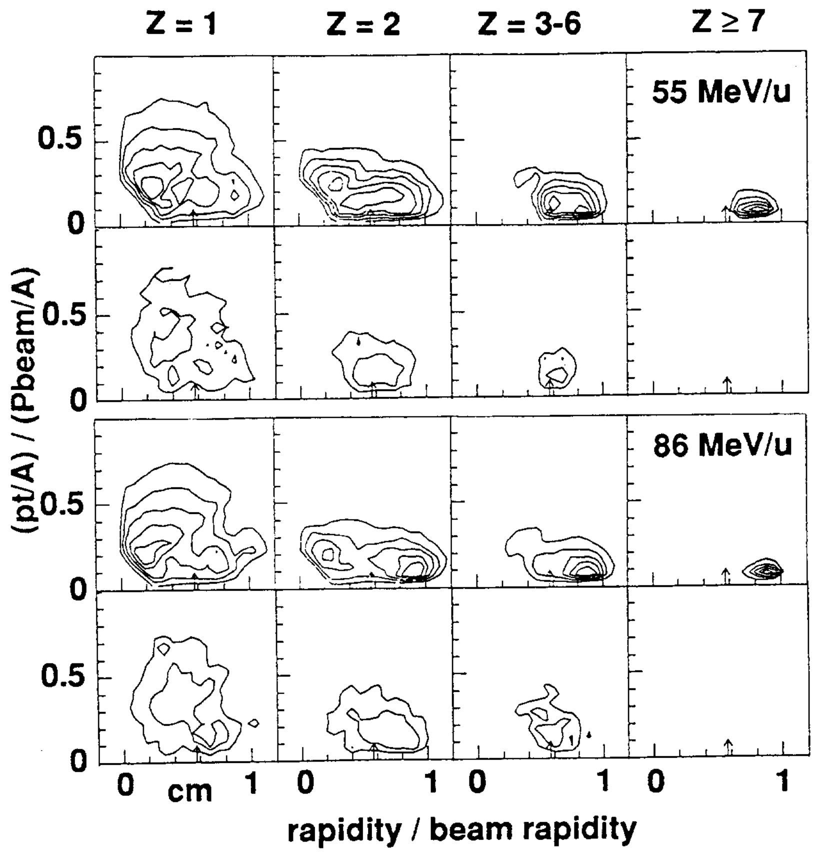


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