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June 1995

LPCC 95-12

Submitted to Physics Letters B

INSTITUT NATIONAL
DE PHYSIQUE NUCLEAIRE ET DE PHYSIQUE DES PARTICULES

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

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ONSET OF COLLECTIVE EXPANSION IN NUCLEUS-NUCLEUS COLLISIONS BELOW 100 MeV/u *)

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Abstract : In ^{36}Ar + ^{27}Al reactions at bombarding energies E/A from 55 to 95 MeV, the mass and excitation energy of the quasi-projectile have been reconstructed at all impact parameters. Up to excitation energies E*/A of ~ 5-6 MeV, the mean kinetic energies of Z=1 to Z=9 fragments are in agreement with values predicted by sequential statistical decay. Above, a collective expansion energy is needed that grows with E*/A, reaching 1 MeV/u at E*/A ~10 MeV. It decreases with the fragment charge.

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*) *Experiment performed at the GANIL facility, Caen.*

The study of central nucleus-nucleus collisions at energies up to E_{beam}/A = 150 MeV revealed recently that a large part (up to one half) of the available energy can be released as collective expansion, presumably following compression at the initial stage of the collision. For nuclei formed in central collisions of ^{40}Ca on ^{40}Ca at E_{beam}/A = 35 MeV, a total excitation energy per nucleon of 6 MeV was calculated. The pattern of correlations in the charge distribution can be reproduced with the sequencial decay model of an expanding nucleus [1] with an expansion energy in the range of 0.5-1 MeV/nucleon [2]. A higher value of 3.5 MeV/nucleon has been obtained in reactions of ^{32}S on ^{27}Al at E_{beam}/A = 37.5 MeV. This expansion energy, combined with a temperature of 8.8 MeV, was needed to reproduce the momentum distribution of the largest fragment and the relative velocities of Intermediate Mass Fragments (IMF's) [3]. For a much heavier system, ^{197}Au on ^{197}Au, at incident energies of 150 MeV/nucleon, expansion energies per nucleon (E_{expan}/A) around or greater than 10 MeV have been deduced by studying the mean kinetic energy of IMF's [4]. On the same system at E_{beam}/A = 100 MeV, a study of the kinetic energy spectra of IMF's led to values between 8 and 13 MeV, decreasing with the fragment charge [5]. In ref. [4], a larger value of E_{expan}/A had also been noted for Z=3. Reactions induced by ^{16}O, ^{36}Ar and ^{84}Kr at energies ranging from E_{beam}/A = 50 to 220 MeV on Ag/Br have been studied with emulsions [6, 7, 8] and expansion energies of 3 to 10 MeV/nucleon have been deduced. This collective expansion is connected with the observation of an increasing multiplicity of IMF's.

In order to investigate the onset of collective expansion and determine the relevant parameters (incident energy, impact parameter, total excitation energy) we have used the data obtained in collisions of ^{36}Ar on ^{27}Al at energies E_{beam}/A ranging from 55 to 95 MeV .

The experiments were performed at the GANIL facility in the reaction chamber Nautilus. Charged products were detected in a nearly 4π geometry using two complementary multidetector systems MUR and TONNEAU. 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 [10]. In addition, 7 large solid angle silicon telescopes were installed 60 cm from the target ; they covered polar angles from 3° to 30° on an azimuthal range of 22° .

A minimum bias trigger was used in which all events with a multiplicity larger than 1 were recorded. For MUR and TONNEAU the velocities of particles and fragments were measured and the corresponding charges identified up to Z=9 using the energy-loss versus time-of-flight technique (up to $Z=3$ for particles which stopped in the scintillator). For the telescopes, kinetic energies and charges were derived from the ΔE-E measurement. Since the kinematic analysis relies on velocities, 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 first step in the analysis was to select the well characterized events as in ref. 10, 17. The next step was to sort the events as a function of the violence of the collision. For this purpose, the sum of transverse momenta moduli, $P_\perp$, is a very effective global variable especially for the most dissipative collisions which are not contaminated by other events. Indeed, when one particle is missed in an event, $P_\perp$ decreases and the collision appears to be less dissipative, i.e. less central. Assuming a geometrical correspondance between $P_\perp$ and the impact parameter, the cross section of each $P_\perp$ bin can be expressed as an experimentally determined impact parameter, b_{exp}. According to [9] and simulations based on QMD calculations [17], the correlation between b_{exp} and the true impact parameter b has a FWHM of 1-2 fm.

Apart from a small cross section (<30 mb) which can be attributed to incomplete fusion, the reactions which occur for all impact parameters are binary dissipative collisions accompanied by light particle emission from the interaction zone (mid-rapidity source) [15-19]. This is very close to deep inelastic collisions known at lower energies, with two differences : i) the whole range of impact parameters is concerned here, and ii) the quasi-projectile and quasi-target are accompanied by pre-equilibrium emission. This can be called participant-spectator process, but one should keep in mind that here most of the dissipated energy is found as excitation energies of the "spectators" [17-19].

Since all products from the quasi-projectile have velocities well above the detection threshold, we could reconstruct its charge, velocity vector and excitation energy and study its de-excitation. An improvement over ref. [10] was to select those events in which the heaviest fragment is detected in a telescope, thus ensuring a good kinematical reconstruction of the excited primary nucleus in peripheral and semi-peripheral collisions. For central collisions, the use of the telescopes does not make any difference, since almost all products have a charge < 10 and are identified by MUR and TONNEAU. The source velocity vector was reconstructed for each event from the momentum vectors of its products with $Z\geq2$. A cut on $\beta_{//}$ around β_{cm} eliminated most particles from other sources and retained most of the products from the quasi-projectile. A variation of ± 10% on the value of this operational cut was found to have a negligible effect on the results. All detected $Z>3$ products originated from the quasi-projectile.

The charge of the quasi-projectile was reconstructed by adding up the charges of the detected products and taking into account the geometrical efficiency. As in [10], the best way of minimizing the contribution of pre-equilibrium particles was to take for each event the charges of the products emitted in the forward hemisphere in the rest frame of the quasi-projectile and multiply them by 2 in order to get the contribution over 4π. This reconstructed charge is slightly smaller than the projectile charge at all impact parameters, in agreement with the binary character of the collision [15-19] .

The excitation energy E^* of the quasi-projectile was obtained by calorimetry, whereby one sums the kinetic energies of its products in its rest frame and takes into account the mass balance. The mass number for each charge and the contribution of neutrons were determined as in ref. [10]. The contribution of other sources was minimized by taking only the particles in the forward 2π. The mean value (per impact parameter bin) of the excitation energy per nucleon E^*/A varies from ~2 MeV in semi-peripheral collisions (~6 fm) up to ~8 MeV in central collisions at $E_{beam} = 55$ MeV/u and ~11 MeV at $E_{beam} = 95$ MeV/u. It should be noted that these are mean values and that the bin of central collisions corresponds to 70 mb ($b_{exp} < 1.5$ fm, i.e. 0.2 b_{max}) ; a more stringent selection could likely select events with larger E^*/A values (and larger values of expansion energies).

We found that E^*/A is the parameter which essentially determines the de-excitation process. Indeed, the charge distributions of final products Z strongly vary from peripheral collisions (with one heavy fragment close to the projectile) to central collisions (distribution decreasing rapidly from $Z = 1$-2 to $Z \sim 9$), but for the same E^*/A value obtained for different sets of b_{exp} and E_{beam} the charge distributions are the same [19].

This is true also for the kinetic properties of these products, as is shown by looking at their mean kinetic energy in the quasi-projectile frame, $<E_K>$. The variation of $<E_K>$ with Z for six bins of $<E^*/A>$ is displayed in fig. 1. Only the high incident energies reach the highest excitation energy bins. It is seen that the values of $<E_K>$ are nearly independent of the incident energy in each E^*/A bin. The influence of the impact parameter will be discussed later.

These data were compared to de-excitation codes. The code Eugene [11] was used to simulate the reactions on the whole range of impact parameters. For sequential statistical decay without expansion, the Transition State Model was used with three parametrizations of the level density parameter : $a = A/8$ and $A/13$, and $a = f(A)$ according to ref. [12]. These simulated events were sorted and analyzed like the experimental data to obtain b_{exp}, E^*/A, E_K and Z distributions. The values of $<E^*/A>$ in each b_{exp} bin are in agreement with the experimental data. A/8 and A/13 give a good fit of the total multiplicity increase with E^*/A but no prescription reproduces the behaviors of specific products. While too many $Z = 1$ are predicted to be emitted, the multiplicities of $Z = 2$ and heavier fragments are underestimated [19].

In fig. 1, $<E_K>$ is calculated with $a = A/13$, which give the lesser disagreement with the Z distribution and give the largest $<E_K>$ values. The calculated values increase with the excitation energy, since they are related to the temperature of the emitter. They agree with the data up to $<E^*/A> = 5\text{-}6$ MeV. Above these excitation energies, the data for $Z = 1$ are still reproduced, but the disagreement with the other data increases very rapidly with E^*/A and Z. This suggests the existence of a collective expansion, since it gives a larger boost to heavier fragments.

The expansion velocity values which are necessary to fit the data were determined by the following procedure : for each $<E^*/A>$ value and each Z, the total excitation energy was shared among thermal energy and radial expansion energy E_{expan} and the sharing was chosen so that the combination of the thermal kinetic energy (obtained from Eugene) and the expansion energy fits the measured value of $<E_K(Z)>$. Fig. 2 shows the results obtained for the highest excitation energy. For $Z=1$ the value of E_{expan}/A cannot be determined since many of these particles (mostly protons) are emitted by the initial fragments in all directions and the expansion energy is a small fraction of the thermal energy. The value obtained for $Z=2$ (mostly α-particles) is subject to a large error, since these particles are a mixture of initial light fragments and particles emitted by heavy excited fragments. The value of E_{expan}/A decreases with the fragment charge as in ref. [5]. If the fragments are produced simultaneously [1, 13, 14], self-similar expansion (velocity increasing with the distance of the fragment to the center of the expanding system) means that the slow heavy fragments originate from the more dense inner region of the expanding system, as suggested in [5].

The code WIX [13] has been used for E^*/A above 9.5 MeV/nucleon. WIX is the modified version of the statistical multifragmentation code FREESCO [14] in two respects : i) - the interfragment Coulomb trajectory calculation during the expansion is considered and ii) - the collective expansion is incorporated in the form of a homogeneous, though not necessarily isotropic, expansion. It simulates the final stage of the reaction with a simultaneous disassembly of the system with an excitation energy given as input. We assumed that the fragments of the disassembling system are localized within a diluted volume with density $\rho/\rho_0 = 0.3$. The values of $<E_K(Z)>$ obtained without expansion were lower than the values obtained with Eugene, especially for IMF's (Z=3-6). In consequence the expansion energies per nucleon needed to fit the data were much higher.

Other calculations were made using the code SIMON [19] which assumes a multifragmentation process (explosion) : fragments of various sizes are placed in an initial spherical volume with an initial distance between the fragments (freeze-out volume). Several distributions of initial fragments were taken at random. The results are very close to those of WIX.

WIX and SIMON dit not reproduce the charge distributions better than Eugene. Their limitation, compared to Eugene, was the absence of the entrance channel. It was not possible to sort events as a function of $P_\perp$, to reconstruct the quasi-projectile and to calculate the excitation energy like for the experimental data. Therefore the values obtained from the full simulation made with Eugene are more reliable.

At E*/A above ~5 MeV, we observed that the measured distributions of fragments Z from the quasi-projectile decreases very rapidly with increasing Z [18]. Therefore the average value of $<E_{expan}/A>$ in each <E*/A> bin is very close to the value which fits $<E_K>$ of light IMF's. This value is plotted in Fig. 3. The interesting point is the onset of $<E_{expan}/A>$ when the excitation energy exceeds 5-6 MeV per nucleon. At E*/A = 10 MeV/u, it is ~1 MeV/u, i.e. 10% of the excitation energy is released as expansion energy.

WIX and SIMON give the same trends as those seen in Fig. 2 ($E_{expan}/A(Z)$ decreases with Z) and Fig. 3 (onset of expansion energy around E*/A = 5-6 MeV), but the values of $E_{expan}/A(Z)$ and $<E_{expan}/A>$ are about twice higher than those shown in Fig. 2 and 3.

The values of Fig. 3 can be compared to recent experimental data examined as a function of increasing projectile mass and energy. With light projectiles, C and O, non-significant signals of expansion were observed at bombarding energies 60-220 MeV/u on Ag/Br targets [8]. The same conclusion was reached for nuclei formed in ^{84}Kr+^{197}Au collisions with E*/A ~ 5 MeV [21], in agreement with Fig. 3. For central collisions of ^{40}Ca on ^{40}Ca at 35 MeV/u, the expansion energy in the range 0.5-1 MeV/u [2] for E*/A ~6 MeV/u is larger than our values, but not outside uncertainties due to experimental errors and different analysis methods. For Zn+Ti at E_{beam} = 79 A MeV, expansion energies per nucleon around 2.5 MeV have been obtained with WIX at E*/A ~12 MeV [17], in agreement with our results. The value of 3.5 MeV/u obtained in reactions of ^{32}S on ^{27}Al at 37.5 MeV/u is definitely much larger than the values obtained here, but it could be affected by the binary character of the reaction [15-19]. With ^{36}Ar projectiles on Ag/Br at a bombarding energy of 65±15 A MeV, larger expansion energies (3 MeV/nucleon) have been deduced in central collisions [6]. With ^{84}Kr projectiles at bombarding energies 70-220 MeV/u, the value of $<E_{expan}/A>$ rises to 10 MeV and possibly 20 MeV [7, 8]. For the much heavier system ^{197}Au on ^{197}Au at incident energies of 100-150 A MeV, E_{expan}/A values around or greater than 10 MeV were obtained [4, 5]. Clearly larger systems and higher beam energies lead to larger values for both <E*/A> and $<E_{expan}/A>$.

It should be noted that these high values of $<E_{expan}/A>$ were obtained in very central collisions and concern a source located at the center-of-mass. This source is either a participant source accompanied by two "spectators" [4, 5], or a single source (fusion or full stopping events) [7, 8], whereas our data concern the expansion energy of a "spectator".

The expansion energy could come from compression in the interaction zone during the first stage of the nucleus-nucleus encounter, which would propagate inside the quasi-projectile and quasi-target. Since the size of the interaction zone increases with the centrality of the collision, one would expect an increase of $<E_K>$ values when the impact parameter decreases, for collisions having the same E*/A value. Such a comparison is possible by using different beam energies. At low <E*/A> values, where expansion is weak or zero, no influence of the impact parameter can be seen in Fig. 1. At <E*/A> = 7.5-8.5 MeV the data obtained at 55 MeV/u come from $b_{exp} < 1.5$ fm and are above the data obtained at 67 MeV/u with $b_{exp} = 1.5$-2.5 fm and at 95 MeV/u with $b_{exp} = 2.5$-3.5 fm. A similar observation is made at <E*/A> = 8.5-9.5 where the 67 MeV/u values come from $b_{exp} < 1.5$ fm and are slightly larger than the values obtained at 86 and 95 MeV/u, both with $b_{exp} = 1.5$-2.5 fm. Such a comparison cannot be made at E*/A> 10 MeV, since all data come from $b_{exp} < 1.5$ fm. This decrease with the impact parameter, however, is not large and is not necessarily related to compression. Other effects, such as the variation of the quasi-projectile charge and mass and its deformation after separation from the quasi-target, might be responsible for the observed trend.

This onset of expansion of the hot nuclei is coupled to a fast increase of the rate of IMF's produced in the decay of these nuclei [19]. It is therefore tempting to explain these two observations by thermal fragmentation of an expanding nucleus. Such a conclusion has been reached in studying the decay of hot nuclei produced by relativistic light ions [22].

In summary, mean kinetic energies of IMF's produced in ^{36}Ar+^{27}Al collisions at $E_{beam} = 55$-95 MeV/u indicate a radial collective expansion velocity at break-up when the total excitation energy per nucleon of the disassembling quasi-projectile exceeds 5-

6 MeV/u. It decreases with the fragment charge, suggesting that heavy fragments come from a more inner part of the disassembling nucleus. For this light system, the largest expansion energies observed, ~1 MeV/u, represent only ~4% of the kinetic energy available in the c.m. frame, and about one tenth of the excitation energy stored in the disassembling nucleus. The dominant role for the onset and increase of expansion energy is played by the excitation energy, with some influence of the impact parameter.

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FIGURE CAPTIONS

1) Mean kinetic energy of products from the quasi-projectile in its rest frame versus their charge, for several bins of excitation energy per nucleon obtained at different combinations of incident energies and impact parameters. The lines are the results of a simulation of the reaction including sequential statistical decay of the quasi-projectile.

2) Expansion energy per nucleon which fits the mean kinetic energy of the final fragment with charge Z, at $E_{beam}/A = 95$ MeV and for central collisions ($b_{exp} < 1.5$ fm, average total excitation energy 11 MeV/u). The line is to guide the eye. Values obtained with WIX and SIMON are about twice higher.

3) Mean expansion energy per nucleon versus the excitation energy per nucleon of the disassembling quasi-projectile. The line is to guide the eye. Values obtained with WIX and SIMON are about twice higher.

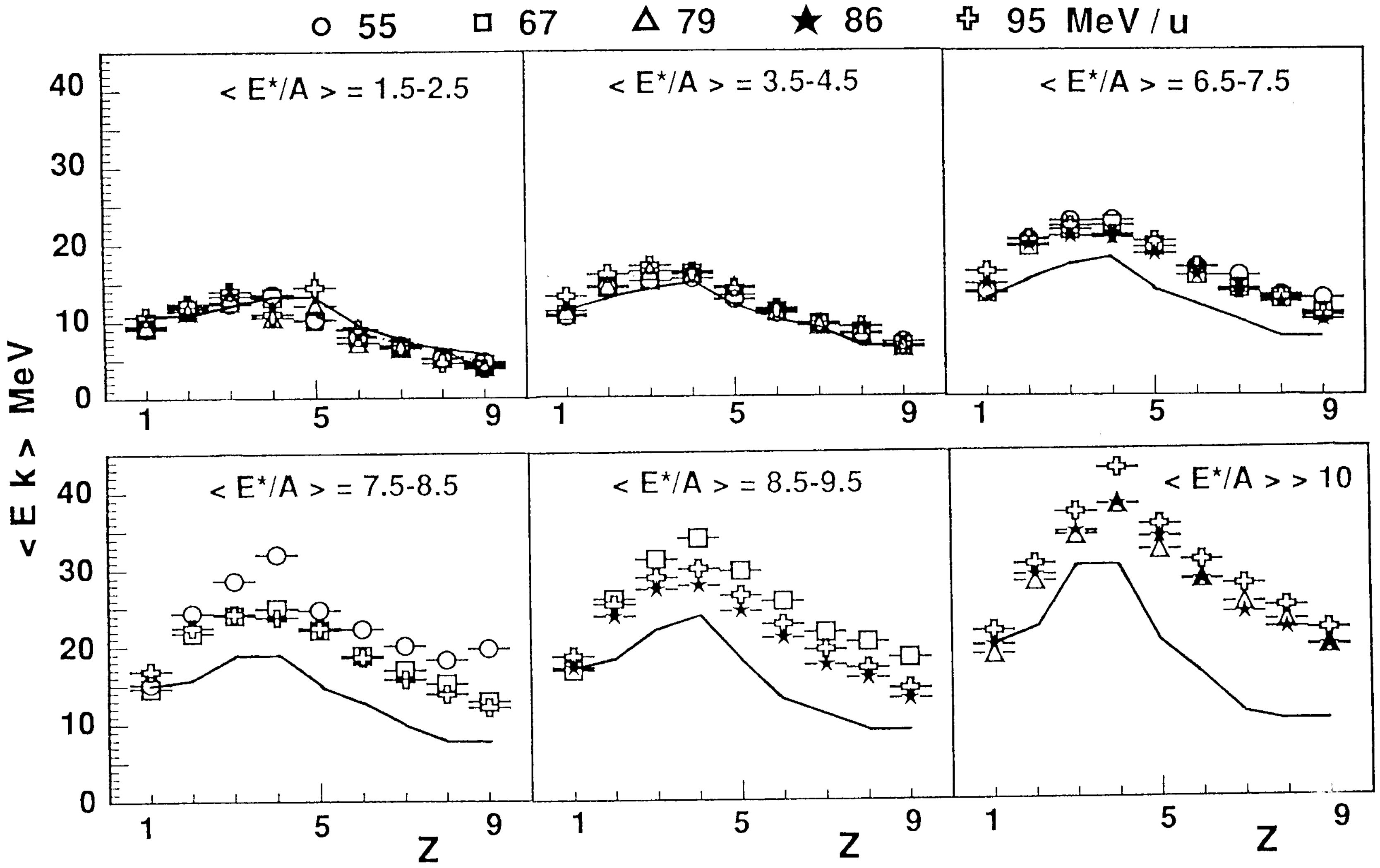
○ 55
□ 67
△ 79
★ 86
✚ 95 MeV / u
< E*/A > = 1.5-2.5
< E*/A > = 3.5-4.5
< E*/A > = 6.5-7.5
< E*/A > = 7.5-8.5
< E*/A > = 8.5-9.5
< E*/A > > 10
< E k > MeV
0
10
20
30
40
1
5
9
Z

Fig 1

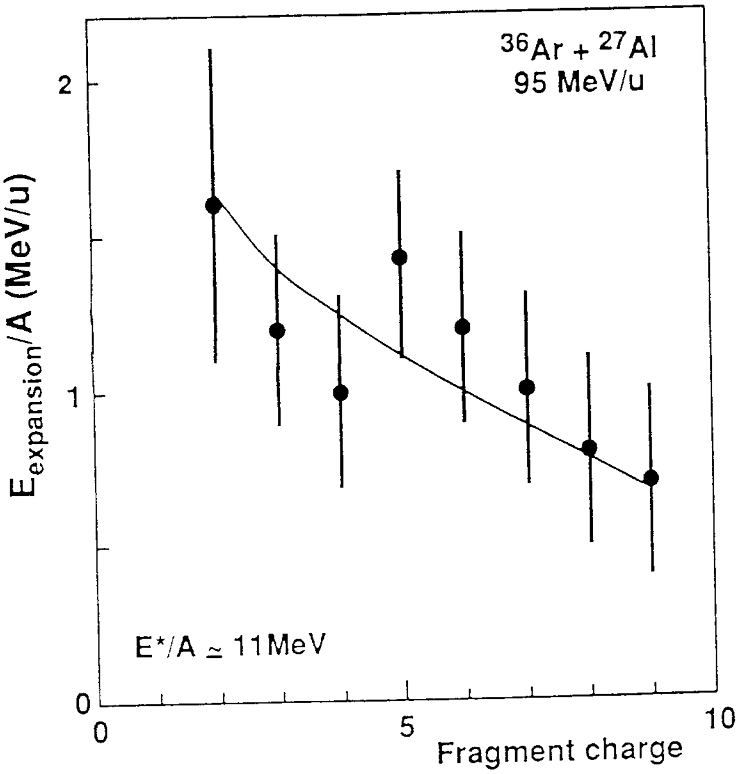
^{36}Ar + ^{27}Al
95 MeV/u
E$_{\text{expansion}}$/A (MeV/u)
E*/A ≃ 11MeV
0
1
2
0
5
10
Fragment charge

Fig. 2

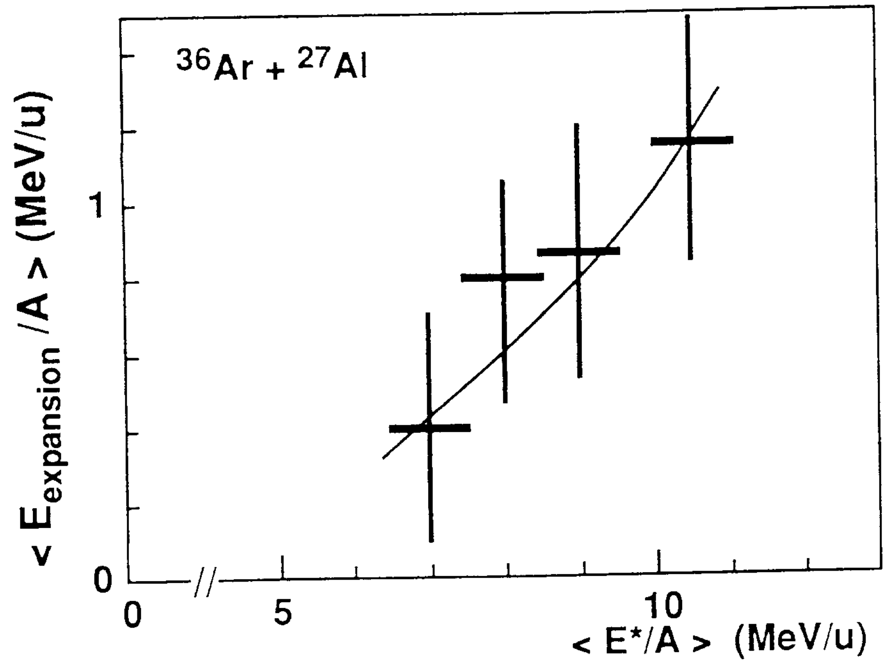
^{36}Ar + ^{27}Al
< E$_{\text{expansion}}$ /A > (MeV/u)
0
1
0
5
10
< E*/A > (MeV/u)

Fig. 3