FERMIONIC MOLECULAR DYNAMICS: MULTIFRAGMENTATION IN HEAVY–ION COLLISIONS AND IN EXCITED NUCLEI

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INTRODUCTION AND SUMMARY

How multifragmentation happens in heavy ion collisions is still a matter of debate. Explanations reach from nucleation over self organization, spinodal decomposition to cold break–up and survival of initial correlations. For an overview see ref. [1]. A key question is the time scale of the reaction. Slow processes like nucleation or self organization are hindered if the expansion of the whole system is too fast. Another issue is the relaxation time for thermal and chemical equilibrium which is important when statistical models are used to explain multifragmentation [2, 3, 4, 5].

If one considers the decay of excited spectator matter which has not been compressed, the expansion preceding the fragmentation might be slow enough to allow for global equilibration. However, below excitations energies of about 6 MeV per nucleon an equilibrated nucleus will most likely cool down by evaporating nucleons but not by breaking into many intermediate mass fragments (IMF, $Z \geq 3$). The reason is that the barrier for multifragmentation is too high and the nucleus has cooled already by evaporation before it fragments into pieces. In order to drive an expansion across the barrier into the spinodal region just by means of thermal excitation at normal density, one needs excitation energies between 6 and 10 MeV per particle [5]. For these energies the question arises: Can in a heavy–ion collision, which chops off a large fraction of the nucleus, the excitation of the remaining spectator part be distributed fast enough among the kinetic degrees of freedom such that the expansion sets in only after thermal equilibration? Or is it more likely that a peripheral or semi–peripheral collision creates a non–equilibrium object with strong local fluctuations, which drive the system across the barrier towards multifragmentation right away without first thermalizing and then expanding? In such a situation a common mean field would not establish anymore and the system could not be regarded as an equilibrated Fermi gas in a mean field.

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We want to argue here that a non–thermal situation is actually very helpful in getting the nucleus across the barrier for multifragmentation which exists in the equilibrium potential–energy surface. On the way to equilibrium the system can then easily cross the equilibrium barriers or is already behind them. A non–equilibrium system can feed into all parts of the coexistence region in the phase diagram, large and small volumes, i.e. many or few fragments. And thus the isotopic ratios in the ensemble can reflect the properties of the coexistence region and the liquid–gas phase transition [6]. Therefore, we see the possibility that the phase diagram and the liquid–gas phase transition can also be investigated by non–equilibrium multifragmention of a wounded spectator and may be even better than by thermally excited nuclei (hot Fermi gas in a mean–field) which go through thermal expansion and subsequent formation of fragments.

For the participant matter created for example in central collisions the compression is much stronger and the excitation energy much higher. A transient pressure exists during the time of instreaming matter and thereafter due to recoil of promptly emitted particles. This together with the short mean free path at high excitations is in favour of multifragmentation originating from a more thermalized source. But the whole system is expanding and cooling fast so that it is questionable if there are enough collisions to ensure local equilibrium until freeze out. Experiments show for example that a large part of the excitation energy is converted into radial flow [7].

There is little hope to decide upon these questions experimentally in a unique way, because it is very difficult to measure temperature and flow profiles [6, 7, 8] and even harder or impossible to infer experimentally on the time scale of the evolution of the system. Therefore, microscopic transport models which do not assume equilibration are needed for a better understanding. These models should go beyond the mean field approach, which is a kind of equilibrium assumption in itself, so that in principle they are capable to describe many–body correlations like the formation of fragments. QMD, AMD and FMD are molecular dynamics models which assert this claim. How equilibrium is achieved can then be studied by comparing distributions, for example of mass, charge, kinetic energy etc, with equilibrium distributions.

In the following two sections we investigate within Fermionic Molecular Dynamics (FMD) the decay of a compound system with 46 or 80 nucleons which was created in a heavy–ion collision at a beam energy of about 35 AMeV and the decay of ^{56}Fe which we put in an excited state by scaling the whole many–body wave function and/or randomly moving the centroids of the wave packets. For the definition of the model see ref. [9, 10, 11, 12, 13].

The succeeding section shows FMD collisions of ^{19}F + ^{27}Al and ^{40}Ca + ^{40}Ca in the Fermi energy domain where multifragmentation is the dominant reaction mechanism. The system, however, does not go through a thermalized situation. In section 'Decay of excited nuclei' FMD evolutions of randomly excited nuclei (artificially thermalized source inside the multifragmentation barrier) are investigated. They do not show multifragmentation within a set of about 20 runs. Either they vapourize into individual nucleons, or after expanding and blowing off outer layers the inner part contracts again and an evaporation residue, which can be rather small, is left over. Only if not all correlations are destroyed the excited nucleus expands and decays into fragments and single nucleons, quite similar to the decay following the collision.

MULTIFRAGMENTATION IN COLLISIONS

Central and semi–peripheral collisions of ^{19}F + ^{27}Al and ^{40}Ca + ^{40}Ca calculated within FMD are shown in fig. 1 and 2. We choose an energy of 32 AMeV and 35 AMeV for which the relative velocity between the two nuclei is about the Fermi velocity. Here we expect the break down of the mean–field picture which prevails in the dissipative regime (up to about $E_{beam} = 15A$MeV) where the system either fuses or undergoes a strongly damped binary collision [12]. When the collective velocity becomes comparable to the internal velocities of the nucleons, a common mean field cannot be established any longer and non–equilibrium effects will be important. The picture of a hot Fermi gas in a mean field will no longer be true.

The following figures show a variety of events as contour plots of the one–body density in coordinate space. This density is integrated over the z–direction. Figure 1 and 2 present runs at two impact parameters and two initial orientations of the intrinsically deformed ground states.

In fig. 1 one sees for both impact parameters the creation of a source which lives for about 100 fm/c before it fragments into pieces of all sizes. The time is given in the upper right corners. For the larger impact parameter the source is more stretched and the final momenta of the fragments are not as isotropic as in central collision.

For the larger system ^{40}Ca + ^{40}Ca (fig. 2) the situation is similar except that the number of IMFs is larger and at impact parameter $b = 2.75$ fm the outgoing fragments have still a more isotropic momentum distribution. Pronounced flow sets in for larger impact parameters.

Although the one–body densities at $t = 100$ fm/c in fig. 1 and at $t = 120$ fm/c in fig. 2 look very thermalized, they are not. There are still strong many–body correlations which just cannot be seen in a one–body distribution. Analyzing the time evolution of a cluster one sees that the correlations between the wave packets which finally compose the fragment can be followed back for rather long time. The heavy–ion collision does not completely randomize the many–body state. The important role of correlations for multifragmentation in FMD will be discussed further in the following section where we destroy these correlations artificially.

DECAY OF EXCITED NUCLEI

In order to study the influence of many–body correlations on the decay pattern of an excited nuclear system we create in this section various initial states by exciting a ^{56}Fe nucleus through a combination of scaling the ground–state density and randomly displacing the mean positions of the wave packets without changing the density. Both create excitation, but while the scaling does not destroy the inter–particle correlations, the random displacement does.

In the FMD ground state the wave packets arrange in phase space such that the total energy is minimized. This ground state is an intrinsic state in which the relative positions and orientations of the wave packets in coordinate and momentum space reflect many–body correlations. If one destroys these correlations by randomly displacing all mean position parameters $\vec{r}_k$ around their original positions within a small circle of radius 0.2 fm perpendicular to $\vec{r}_k$ the ^{56}Fe nucleus achieves already 1.6 MeV excitation energy per particle, although the one–body density remains practically unchanged. The

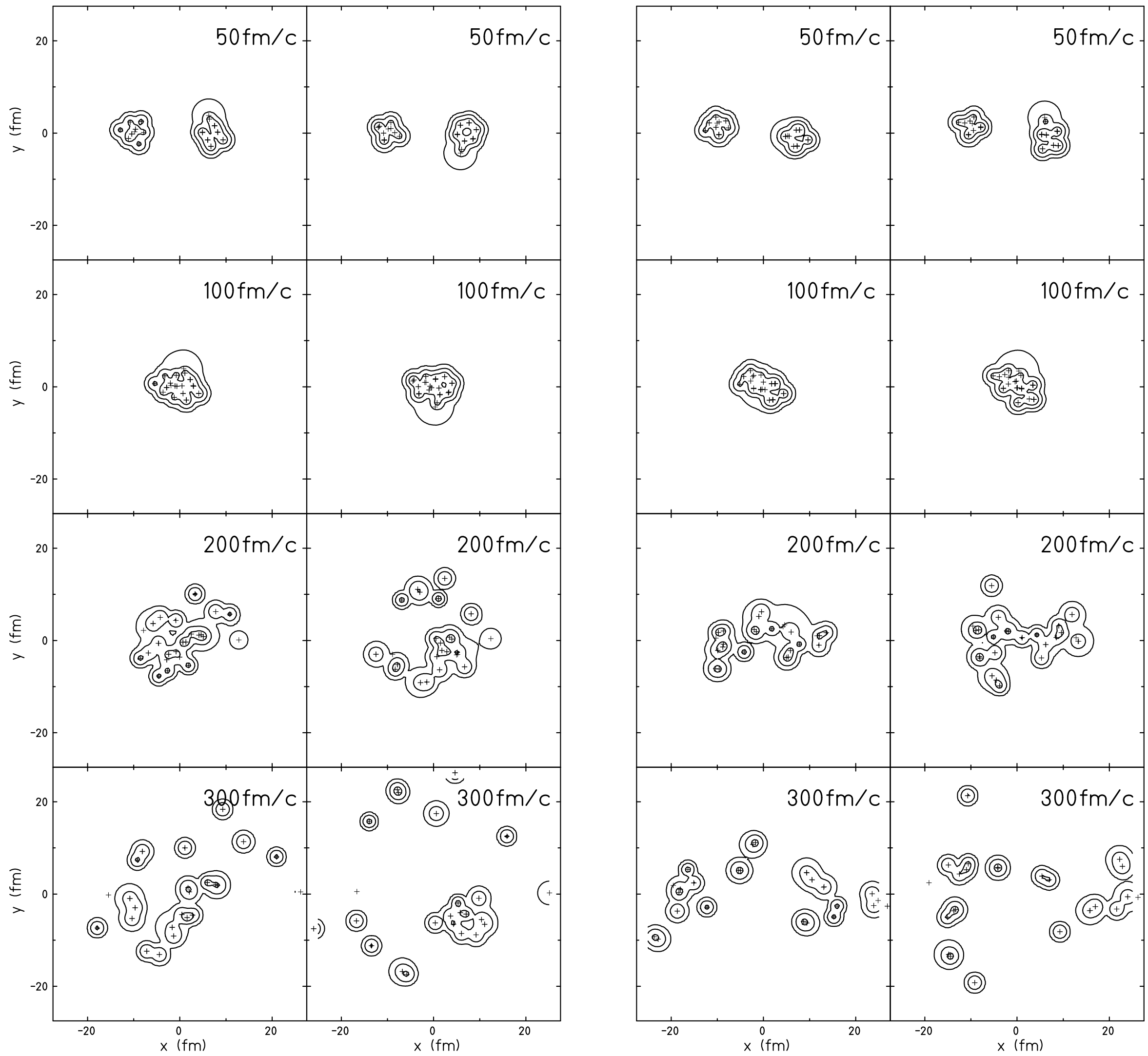

Figure 1. One–body density in coordinate space integrated over z for $^{19}F+^{27}Al$ collisions at 32 AMeV, $b = 0.5$ fm (l.h.s.) and $b = 2.5$ fm (r.h.s.). The contour lines depict the density at 0.01, 0.1, 0.5 fm^{-2}. Crosses indicate the mean positions $\vec{r}_k$ of the wave packets.

first row in fig. 3 shows the time evolution of an excited state with 9.7 AMeV excitation energy which was achieved by random displacements within 2 fm. One sees a fast expansion of the outer density layers which carries away a lot of energy and the survival of a residue in the center which evaporates nucleons on a longer time scale (not shown here).

In the second row the same magnitude of random displacements leads to 11.2 AMeV excitation energy. Here the expansion is faster and the residue is smaller. But there are also other cases around 11.2 AMeV where no residue is left over. Already above $E^* = 12$ AMeV no residues are observed anymore and the nucleus vaporizes completely. There is a sharp transition around $E^* = 11$ AMeV where the thermal expansion can not be brought to a halt by the attractive interaction anymore.

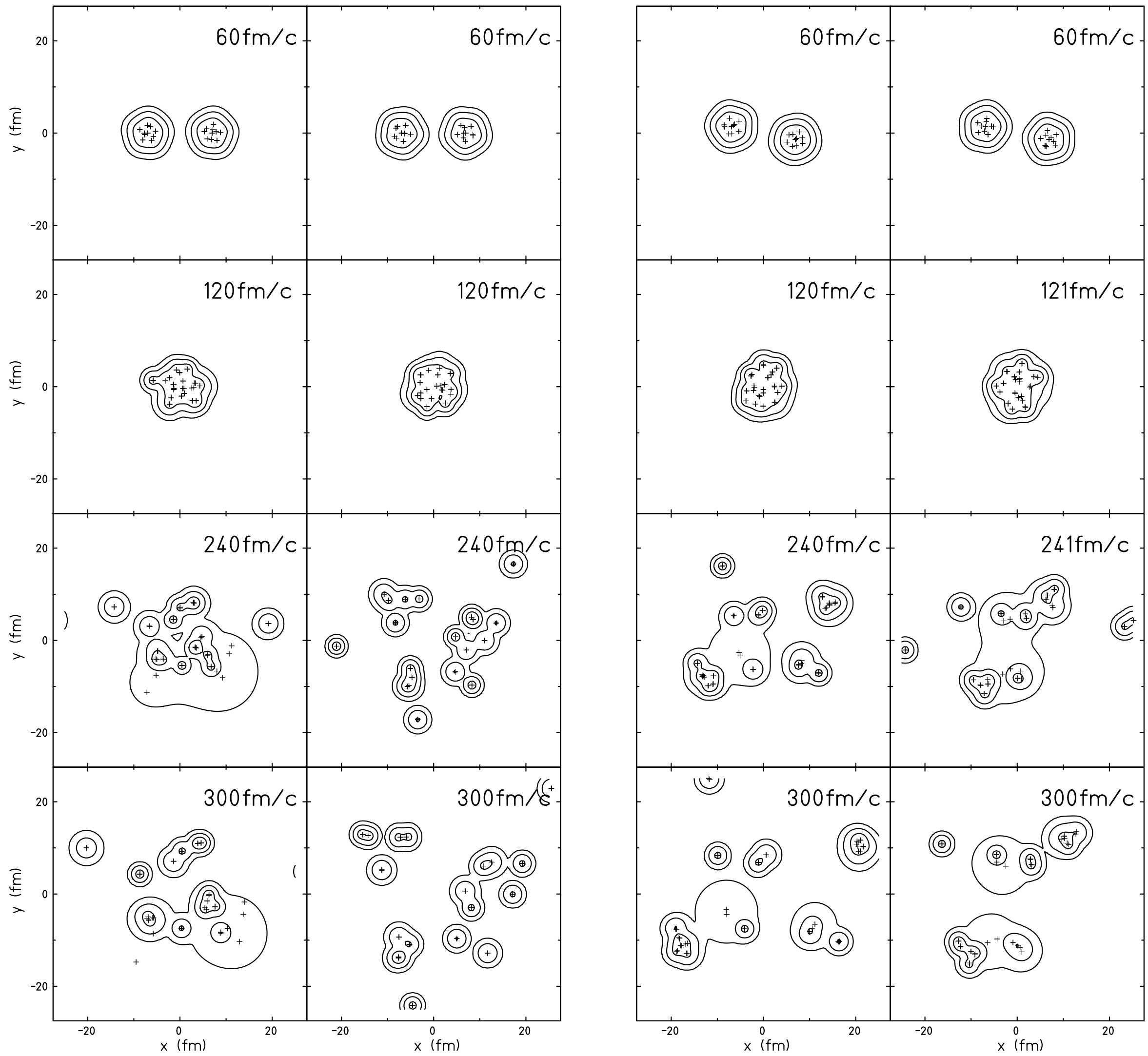

Figure 2. Same as fig. 1 but for ^{40}Ca+^{40}Ca collisions at 35 AMeV, $b = 0.25$ fm (l.h.s) and $b = 2.75$ fm (r.h.s).

In the fourth row we scaled the density in coordinate space by a factor 2.2, which implies a scaling of the momentum density by 1/2.2, and in addition displaced the mean position vectors within 0.5 fm. The result is an excitation energy of $E^* =$ 11.3 AMeV similar to the randomized case in the second row. Up to 200 fm/c also the density develops rather similar to this case. The main difference to random excitation is that the compressed nuclei (by scaling) vaporize mainly by spreading of the wave packets and less by radial motion of the centroids (crosses in fig. 3) whereas in the randomized nuclei the centroids move out faster. At lower excitation energies, i.e. below 10 AMeV (not shown here), a few particles are emitted fast, then the residue goes through damped monopole vibrations while thermalizing, and finally evaporates nucleons after some delay. From this and other runs we conclude that concerning multifragmentation the coherent compression does not change the picture too much compared to random excitation.

The last row shows the evolution of a system in which only the mean position vectors are scaled down by 0.6, but the width parameters and the mean momentum parameters are not changed. On top of that a random displacement within 0.3 fm was applied. The resulting excitation energy $E^* = 10\ A$MeV is comparable with the cases discussed above. But unlike in the first row the system expands without forming a residue in the centre and then undergoes multifragmentation. The reason is that this way of exciting the nucleus does not destroy as much the spatial correlations. Those wave packets which are grouped together in the ground state will still be close after the excitation and the correlations survive to a large extend the expansion. The density develops wrinkles rather early (see frame at 50 fm/c) which rapidly become cracks (see 100 fm/c) and at 200 fm/c, where in the first row the randomized system is still rather compact, the fragments are widely separated. One should note that although the one–body density of the initial state seems perfectly symmetric and no extra momentum has been given to the wave packets the expansion amplifies the correlations and the initial symmetry of the one–body density is broken by rapidly growing fluctuations.

This shows that in FMD many–body correlations play an important role in the formation of fragments. It seems that the time, which is set by the expansion, is too short to allow the many–body state to develop the special kind of many–body correlations which are needed to make a cluster with low enough excitation energy, so that it can survive.

The absence of multifragmentation in other calculations of the FMD type [14, 15] is interesting. Especially in [14] the effect of decoupling the center–of–mass degrees of freedom from the internal degrees of freedom of a fragment was investigated because in a many–body state, which is a (antisymmetrized) product of single–particle packets, a fragment has always about 10 MeV kinetic energy in the localization of the c.m.–coordinate, which for small fragments might decrease the production probability [16]. Even with the additional degrees of freedom no multifragmentation was found in ref. [14].

One must however be very careful in comparing different FMD type calculations because we found that the result of a heavy–ion reaction is very sensitive to the two–body Hamiltonian employed. In particular if the ground state properties of the different fragments are not described well (with the very same Hamiltonian) the outcome of a collision is unpredictable. But even for interactions which reproduce ground states equally well it can happen that for example two light nuclei do not fuse anymore at low energy (a must for any model). Therefore one may not yet conclude that the FMD trial state is too much restricted in its degrees of freedom since we see multifragmentation, dissipative binary reactions and fusion with the same interaction [12].

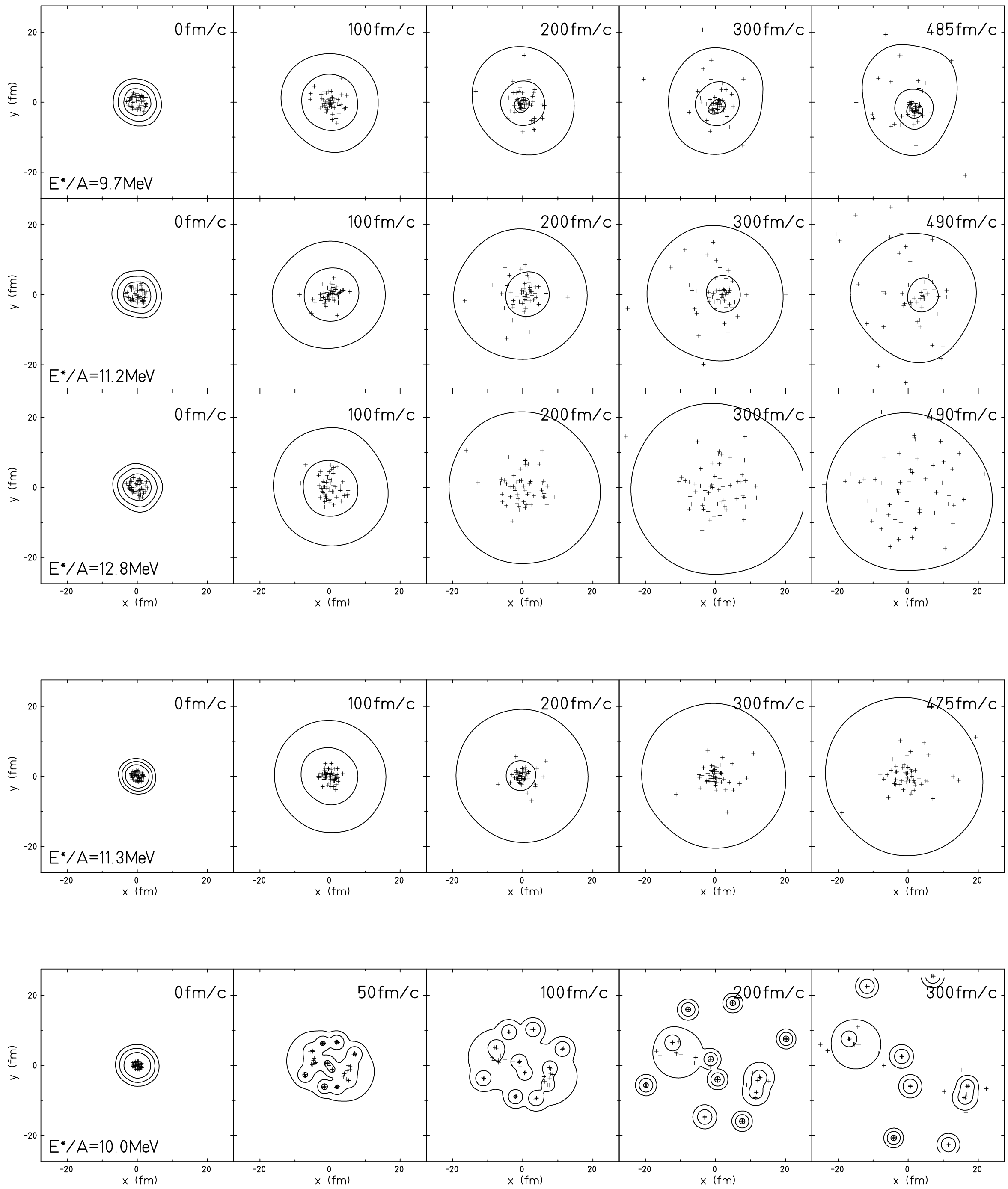

Figure 3. Same as fig. 1 but for ^{56}Fe deexcitations at various excitations. First three rows: random displacement of mean positions $\vec{r}_k$ (crosses). Fourth row: density scaled by 2.2 and small random displacements. Fifth row: $\vec{r}_k \to 0.6\vec{r}_k$ and small random displacements.

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