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XXIX International Winter Meeting on Nuclear Physics Bormio (Italy) 14-19 January 1991

LNS/Ph/91-02

Centre National de la Recherche Scientifique
Commissariat à l'Energie Atomique

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Abstract

We study the stability of excited ^{197}Au nuclei with respect to multifragmentation. For that we use a dynamical simulation based on molecular dynamics and restructured aggregation. A particular attention is paid to check the stability of the "ground state" nuclei generated by the simulation. Four kinds of excitations are considered : heat, compression, rotation and a geometrical instability created when a projectile drills a hole in a ^{197}Au nucleus.

In high energy proton induced reactions as well as in heavy ion collisions nuclei can break up into pieces if enough excitation energy is available. This process is called multifragmentation [1]. The disassembly of an excited nucleus is closely related to the fact that nuclear forces are of short range. In a central collision between two heavy ions, the hot and compressed system which is formed at the beginning of the collision expands. If the expansion is large enough, the density of the system can become so low that the nucleons which are close enough from one another form a cluster and separate from the rest of the system. This is due to the short range nuclear

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nucleus to multifragmentation occurs between 3 and 5 MeV/u. The critical value

attraction. If such a situation is reached, the system becomes highly unstable because the charged clusters repel each other : the system undergoes multifragmentation.

Two families of approaches try to understand nuclear multifragmentation in the recent years :

- Static ones [2–3] in which one studies the stability of a nucleus in a low density configuration. This state is expected to be formed in a proton–nucleus or nucleus–nucleus collision .
- Dynamical ones [4–12] where one tries to follow the evolution either of an initial hot and compressed system or, even better, to describe the collision of two heavy ions from the beginning to the end.

The main difficulty to describe nuclear multifragmentation is that one has to deal with a many body problem in all its complexity. Dynamical mean field theories are quite successful to describe one body observables but fail in describing the formation of clusters. Attempts have been made to extend them in a phenomenological way in order to take care of the correlations which are important for the multifragmentation process. This was the philosophy proposed in ref.[7] and used with different models in refs.[10–12]. The basic idea is that a mean field description is sufficient to describe the collision of two heavy ions when the fluctuations of the mean field are small. The magnitude of the latter are evaluated at each step of the one body dynamical calculation using percolation methods. If they become large, the system becomes unstable with respect to multifragmentation. One of the most sophisticated model in this respect is the one of ref.[10] which uses a kinetic Landau-Vlasov equation coupled to a restructured aggregation model. This description has allowed to reproduce satisfactorily number of experimental results about multifragmentation. Nevertheless, one uses initially a one body theory while it would be desirable to use a N-body approach from the very beginning.

Of course one cannot solve exactly a N-body problem and one has to make strong approximations. If we are mainly interested in nuclear multifragmentation, molecular dynamics is a crude but useful description. This method has been used in the past in ref.[4–6] with schematic interactions between the nucleons and several improvements have been done since then. We want to follow this line and use a molecular dynamical approach to describe the evolution of a set of interacting nucleons. In this approach we pay a particular attention to the difference between neutrons (n) and protons (p) since this is an important experimental issue. In addition, we couple the molecular dynamical approach to the restructured aggregation model of ref.[11] which gives an approximate but reasonnable description of cluster formation [13]. The reason for using aggregation is that, at the point of instability, the nucleons aggregate into compact clusters and do not stay as filamented objects which is the case if we restrict to molecular dynamics only.

In this contribution we would like to present some results about an approach of multifragmentation based on molecular dynamics and a restructured aggregation model. We shall investigate this problem in details and show that one can built nuclei which are stable on a time scale which is larger than the time needed for the system to reach the instability region. Then we shall apply this approach to study the stability of isolated nuclei with different initial excitations and compression.

or a ^{40}Ca nucleus. One may note that for $r_h = 4$ fm the mass of the residual nucleus

1 Molecular dynamics

1.1 Description of nucleons

As proposed by other authors [4], we suppose that each nucleon is represented by a gaussian in phase space :

$$f(\vec{r}) = \left(\frac{\alpha}{\sqrt{\pi}}\right)^3 e^{-\alpha^2 r^2} \left(\frac{\beta}{\sqrt{\pi}}\right)^3 e^{-\beta^2 p^2} \quad (1)$$

(in the above formula the center of the nucleon is supposed to be the origin). The parameter α is taken equal to $\alpha = 0.5$ fm^{-1}. This value is chosen such that :

i) the total nuclear density distribution of nuclei, obtained as described below, is in good agreement with the experimental one.
ii) it gives a reasonable binding energy with the chosen effective interaction.

It should be noted that the root mean square radius of the gaussian ($\sqrt{< r^2 >} \approx$ 2.4 fm) is notably larger than the experimental root mean square radius of the nucleon ($\approx$ 0.8 fm). This is not surprising since the gaussian (1) does not represent a free nucleon but aims to simulate a nucleon inside a nucleus. Therefore, it simulates some delocalization of the nucleon due to quantum effects. With $\alpha = 0.5$ fm^{-1} one gets good nuclear density distributions and reasonable binding energies with the effective interaction introduced below. Larger values of α would not lead to reasonably bound nuclei. One may note that the choice of a broad gaussian to represent the nucleons is closely related to the choice of the effective interaction. Indeed, too sharp gaussians lead, locally, to nuclear densities above the normal value and consequently to nuclei which are hardly or even not bound.

The variance of the gaussians in coordinate (σ_r^2) and momentum space (σ_p^2) are related to α and β by : $\sigma_r^2 = 1/2\alpha^2$ and $\sigma_p^2 = 1/2\beta^2$. The parameter β is chosen such that : $\sigma_r^2\,\sigma_p^2 = \hbar^2/4$ (*i.e.* $\alpha\beta = 1/\hbar$). It corresponds to a minimal uncertainty in the gaussian wave packet (1) representing the nucleon. Of course we do not have a quantum mechanical description and this "wave packet" is just useful to evaluate the potential energy of the nucleons as well as the Pauli blocking in case they collide. The value of β ensures that one gets a smooth distribution in momentum space for the whole nucleus. This is important for the Pauli blocking method used for the collisions.

1.2 Interaction between nucleons

The basic ingredient of molecular dynamics is the interaction between nucleons. We use a schematic one deduced from an effective interaction used in time dependent Hartree-Fock calculations [14]. The equation of motion of the nucleons are deduced from the hamiltonian (total energy E) of the system, H, which can be written as :

$$H = E = \sum_i \frac{\mathbf{P}_i^2}{2m} + W \quad (2)$$

Finally, a hole drilled into ^{197}Au nucleus may induce multifra mentation if the mass

Where m is the nucleon mass and $\mathbf{p}_i$ the momentum of the i^{th} nucleon (the sum runs from $i = 1$ to A, the total number of nucleons of the system). The first term corresponds to the kinetic energy of the A particles while the second one is associated to their potential energy. With the choice of our interaction the last term reads :

$$W = E_{Sk} + E_{Yuk} + E_C \tag{3}$$

Where E_{Sk} is the Skyrme energy term, E_{Yuk} a Yukawa interaction and E_C the Coulomb interaction energy. The compressibility associated to this force is $K = 200$ MeV.

1.3 Initial conditions

Before we solve the equations of motion for the particles, we have to prepare an initial configuration of a nucleus of mass A with Z protons and N neutrons. The initial distribution of nucleons in the "ground state" is obtained in two steps. We first generate the position of the nucleons and then sample their momentum.

The position of the center of the gaussian representing the nucleons is obtained by drawing at random A positions inside a sphere of radius $R = 1.14\,A^{1/3}$ with the condition that the distance between any pairs of nucleons of the same type is larger than 1.35 fm ($|\ \mathbf{r}_i - \mathbf{r}_j\ | > 1.35$ fm). This constraint is to ensure a regular paving of the sphere and leads to a density distribution in reasonable agreement with experiment. Fig.1 illustrate this point for the ^{197}Au nucleus. Among the A particles Z are assigned to protons and N to neutrons.

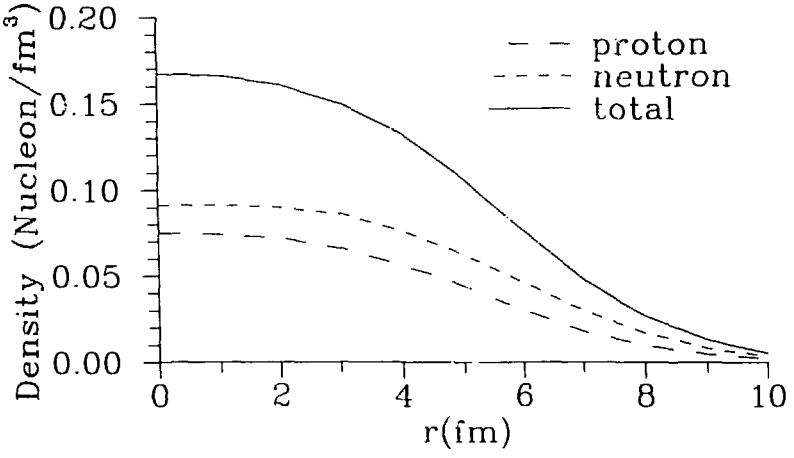

Figure 1: *neutrons, protons and total density profile of the ^{197}Au nucleus generated as described in the text.*

From the previous distribution of nucleons one can calculate the potential energy of the system and the single particle potential $V_{n,p}$, for neutrons and protons, at each

point $\mathbf{r}$:

$$V_{n,p} = \frac{\delta W'}{\delta \rho_{n,p}} \tag{4}$$

It is important to note that W' corresponds to W in which one has subtracted the spurious internal energy of the nucleons which appears due to the effective interaction and the fact that nucleons are represented by gaussians of nuclear matter. This point is important in the context of the stability of "ground state nuclei". For each particle one knows the density $\rho_{n,p}(\mathbf{r})$. Using the local density approximation one can calculate the Fermi momentum $k_F(\mathbf{r})$ at this point and generate a momentum $\mathbf{k}$ for this particle by drawing at random a point inside a sphere of radius k_F. The value of $\mathbf{k}$ is accepted if the particle is bound, *i.e.* if :

$$\frac{\hbar^2 k^2}{2m} + V(\mathbf{r}) < 0 \tag{5}$$

(where $V(\mathbf{r}) = V_n(\mathbf{r})$ or $V_p(\mathbf{r})$ depending upon the particle) otherwise the momentum is rejected and we perform the process again. In the end one can calculate the total binding energy of the system. We find a good order of magnitude compared to experiment. For example, for the ^{197}Au nucleus, one gets a binding energy (for different trials) of about 7.5 MeV/u compared to 7.9 MeV/u experimentally. In all cases the binding energy is a bit smaller than the experimental value. This means that the nucleus is a little bit excited. This is due to condition (5) which requires only that each nucleon is bound but does not ensure that one gets the ground state.

1.4 Dynamical evolution

The equation of motion of the nucleons can be derived from the total hamiltonian H of the system. They read :

$$\frac{d\mathbf{r}_i}{dt} = \frac{\partial H}{\partial \mathbf{p}_i} \quad \text{and} \quad \frac{d\mathbf{p}_i}{dt} = -\frac{\partial H}{\partial \mathbf{r}_i} \tag{6}$$

where $\mathbf{r}_i$ and $\mathbf{p}_i$ are the position and momentum of the i^{th} particle. Given the initial conditions discussed above these equations are solved by the leapfrog method using a time step $\Delta t = 0.3$ fm/c. At each step of the collision we have checked that the total energy of the system is conserved with an accuracy which is always better than 1%. During the evolution of the system nucleons are allowed to collide with a cross section which is different for (nn, pp) and np collisions. In the present work, we have taken the free cross section. The collision between two nucleons is treated in the same way as in ref.[8], *i.e.* two particle collide if their distance is smaller than a distance $d = \sqrt{\sigma/\pi}$, where σ is the corresponding nucleon-nucleon cross section. Since nucleons are fermions, not all the collisions are allowed because of the Pauli blocking. This Pauli blocking is usually treated in an approximate average way. We have used the same method as the one described in ref.[8]

It is worth noting that the collision term is important to excite the intrinsic degrees of freedom. This is illustrated in fig.2 and fig.3 which shows the $Ar + Au$ collision at 20 MeV/u. Fig.2 corresponds to a collision with an impact parameter

$b = 1$ fm and includes collision between nucleons. We observe a "fusion" of part of the projectile and the target. Fig.3 corresponds to a collision with the same impact parameter but with *no collision term* in the equations of motion. One sees that, in this case, the projectile and the target go through each other and interact very little. In particular no energy from the relative motion is transfered into heat.

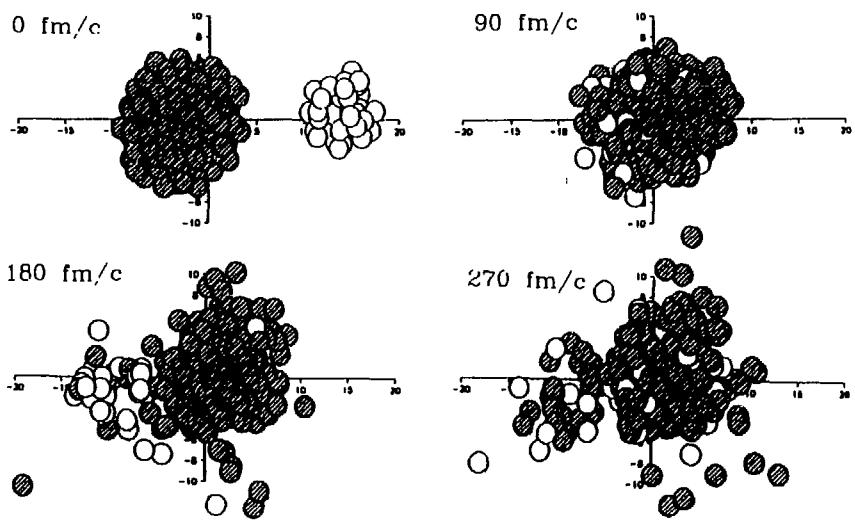

Figure 2: *collision of 20 MeV/u Ar + Au at $b = 1$ fm with collision term.*

1.5 Stability of "ground state" nuclei

Before we use molecular dynamics to calculate some characteristics of the evolution of a nucleus, one has to built and check that this initial configuration is reasonable. Two important tests should be fulfilled :

- The nucleus should remain stable during a time of the order of 100-150 fm/c which corresponds to the time needed in the calculation before one eventually reaches an instability.
- The neutron and proton density distributions as well as their momentum distributions should look reasonable. The first point has been already checked in fig.1.

Using the equation of motion described above we have followed the evolution of a ^{197}Au nucleus as a function of time to see how many nucleons are emitted spontaneously. Since this process is unphysical it should be as small as possible. In fig.4a we show the number of emitted nucleons, divided by the initial mass, as a function of the time t. The results are averaged over a set of initial ^{197}Au nuclei. One observes that, for the time scale we are interested in, less than 4 nucleons are emitted in 200 fm/c. This number is even smaller at 100 fm/c. Since the typical

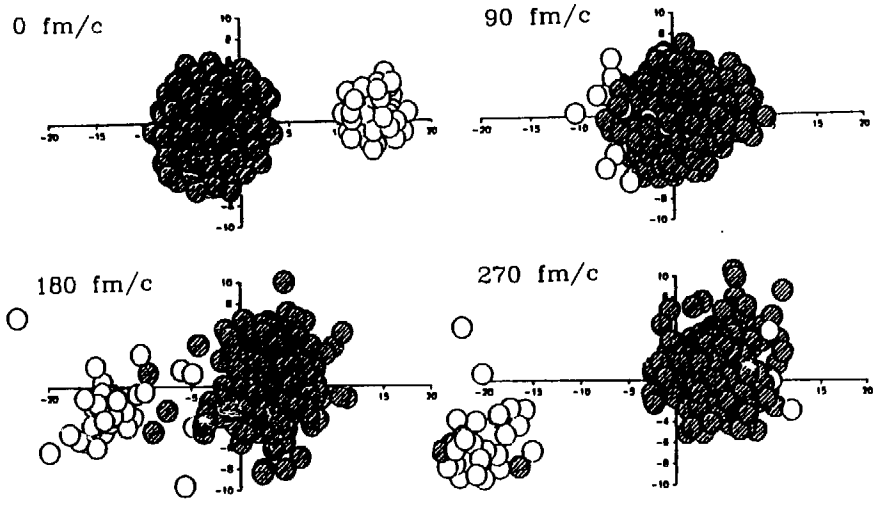

Figure 3: *collision of 20 MeV/u Ar + Au at b = 1 fm without collision term.*

time for multifragmentation is of the order of 60 fm/c, we can safely consider that the prepared nuclei are stable.

Another way to look at this problem is to study the evolution of the root mean square radius of the nucleus as a function of time. Results are displayed in fig.4b for a typical ^{197}Au nucleus. We can see that it does not diverge for large times as it would be the case for a nucleus emitting a lot of nucleons.

Related to the question of stability is the translational invariance of the nucleus, one has to check that if we boost the initial nucleus it still remains stable. Applying a boost velocity of 0.2 c, where c is the velocity of light, we checked that the "ground state" nucleus is stable.

In fig.5 we show, for a typical initial nucleus, the momentum distribution (full curve). The dashed curve corresponds to the distribution obtained using a simple Fermi gas model. Both curves look similar.

Our molecular dynamical model takes care separatly of neutrons and protons. In this respect the interaction between nucleons of different types plays an important role. This is illustrated in fig.6 which shows the evolution of the initial neutron and proton densities as a function of time in the case where we have switch off the isospin part of the interaction. We clearly see that the protons concentrate at the surface while the neutrons go to the interior of the nucleus. Fig.7 show the same evolution with the full effective interaction. Here the neutron and proton densities keep the same shape.

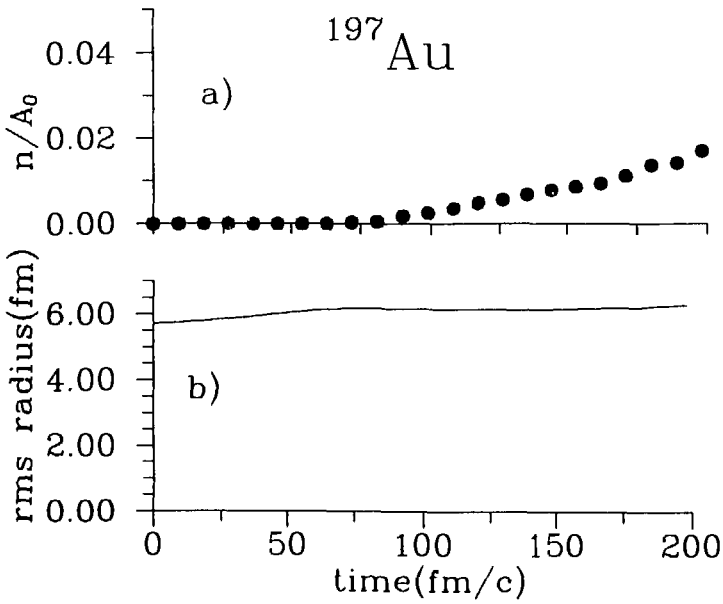

Figure 4: *(a) ratio between the number of emitted particles and the initial mass as a function of time. (b) root mean square radius as a function of t.*

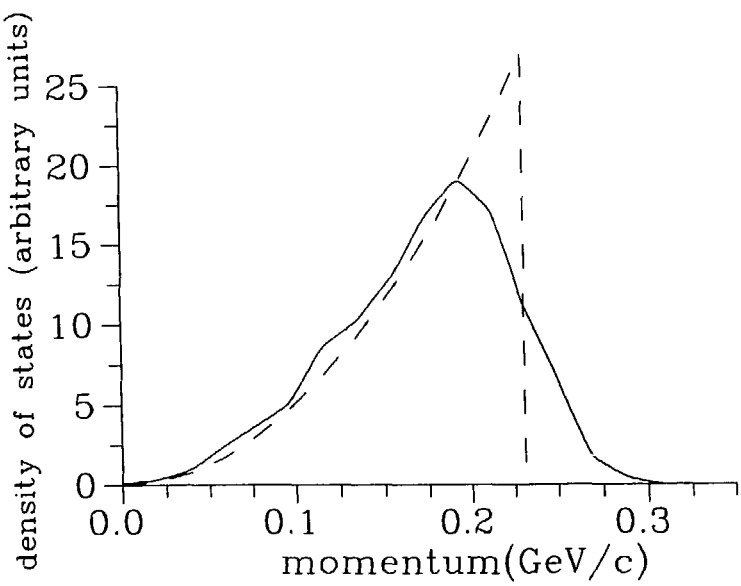

Figure 5: *momentum distribution obtained with the simulation (full line) compared to the momentum distribution of a Fermi gas (dashed line). Unit of the ordinate are arbitrary.*

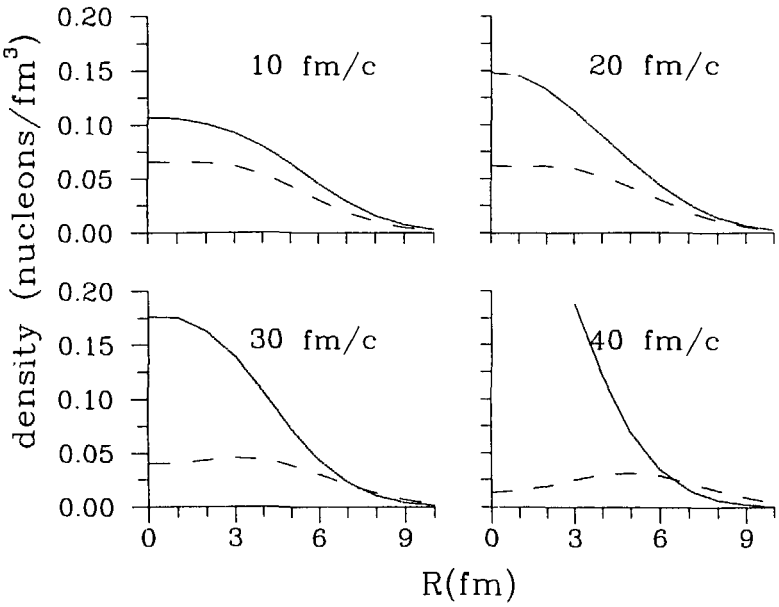

Figure 6: *evolution of the neutron (-) and proton (- -) densities as a function of time in the case where the isospin dependence of the interaction has been switched off.*

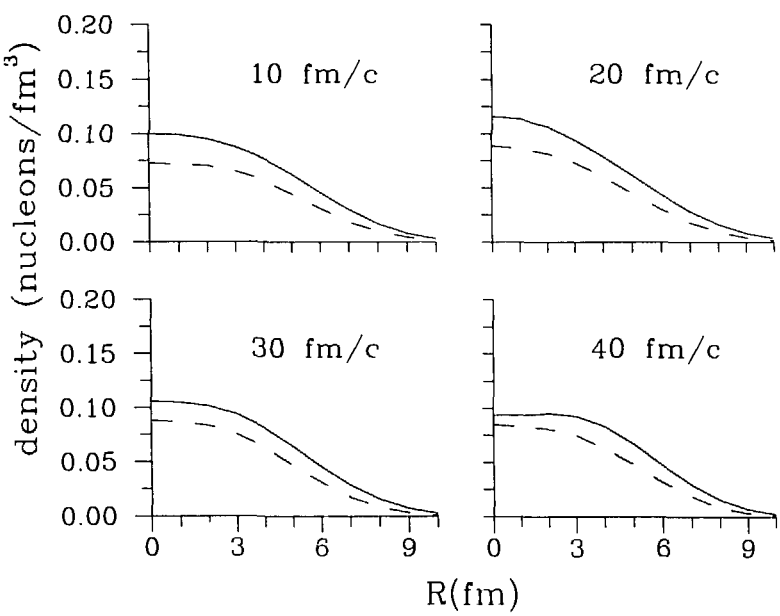

Figure 7: *same as figure 6 with the full effective interaction.*

2 Restructured chromatic aggregation model

The restructured aggregation model proposed in ref.[11] is a simple way to simulate cluster formation. It reproduces, either alone or coupled to dynamical mean field calculations, satisfactorily the main trends of nuclear multifragmentation. In ref.[13] it has been shown, using numerical simulations and comparing the results with emulsion data, that the best agreement is obtained if the aggregation process is performed in 3 dimensions and if a restructuration of the clusters is made. This approach is a simple and schematic method to estimate the fluctuations of the mean field at low densities. The model is static in essence and does not distinguish between neutrons and protons. An important drawback of this last simplification is the existence of clusters made out of neutrons or protons only. This is clearly unphysical and should be cured. The model has been extended in ref.[12] to distinguish between neutrons and protons. We shall refer to this extention as *chromatic aggregation* since the term chromatic is usually employed in the context of percolation to qualify models in which two kinds of particles are present. In this new version we assume that a link betwen two overlapping nucleons exists if they have a different isospin only. In other words, links exist only between neutrons and protons but not between protons–protons or neutrons–neutrons. This hypothesis schematically simulates the stronger attraction which exists between unlike nucleons compared to identical nucleons. The fact that no link can exist between two protons is also due to the Coulomb interaction which tends to repel them and, as a consequence, would break a filamented cluster at that point. The argument does not play for the link between two neutrons. The fact that we assume that there is no link between neutrons is clearly a simplification of reality.

It is interesting to study the influence of these new constraints, compared to the original aggregation model, on the percolation threshold. As in ref.[11] this can be investigated in the framework of the extended liquid drop model. In fig.8 we present the mass distribution of the clusters for 4 different values of the density of a ^{197}Au nucleus.

In fig.9 we show the multifragmentation probability (defined as in ref.[7,11] and as we shall recall it below) as a function of the density of this nucleus. One observes a smooth transition due to the small number of particles present in the system.

In fig.10, the correlation between the atomic number and the mass of the clusters obtained from a density distribution resulting from a molecular dynamical calculation is shown. The full line indicates $N = Z$ while the dashed one is associated to a ratio N/Z equals to the one of the ^{197}Au nucleus. As expected, we get neutron rich nuclei and their distribution in the N–Z plane looks reasonable.

3 Results

We now apply the molecular dynamical approach and the chromatic restructured aggregation model to study the stability of excited nuclei with respect to multifragmentation. In a heavy ion collision one has basically 3 main kinds of excitations :

- *Heat* which corresponds to an incoherent excitation of all the nucleons.

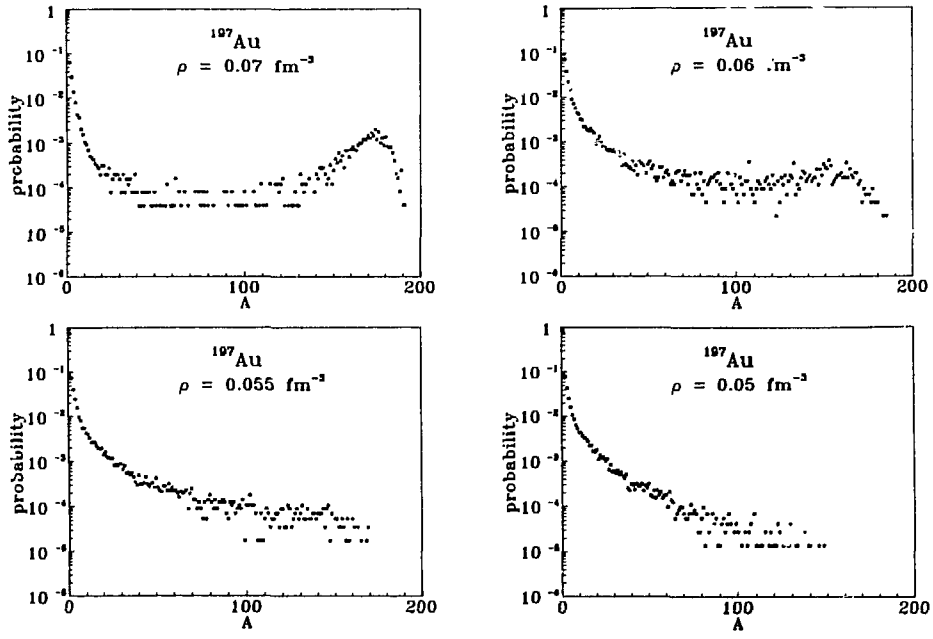

Figure 8: *mass distribution given by the chromatic aggregation model for different values of the initial density of the* ^{197}Au *nucleus.*

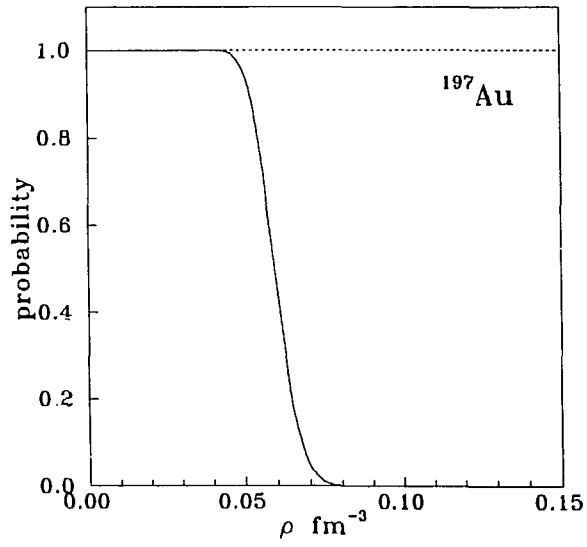

Figure 9: *probability of multifragmentation as a function of the initial density.*

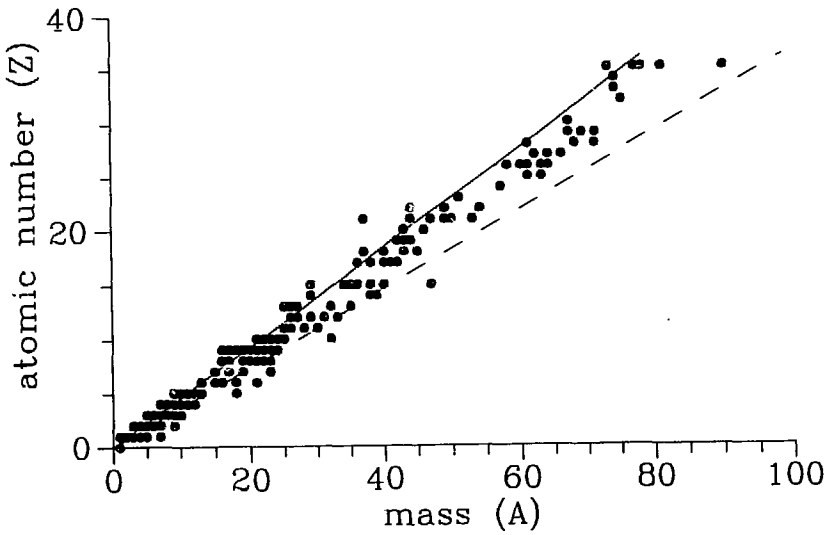

Figure 10: *correlation between the mass A and the atomic number Z obtained by the chromatic restructured aggregation model and the molecular dynamical calculation in a multifragmentation situation.*

- *Compression* which is associated to a collective effect.
- *Rotation* which is also of collective nature and is important for non central collisions.

It is interesting to know the influence of these different types of excitation on the stability of a nucleus. To study this, we prepare an initial nucleus with different kinds of excitation (heat, compression and rotation) and study its stability using our dynamical model. It is of course very schematic to start with a single spherical nucleus and study its dynamical evolution, since a heavy ion collision is by far more complicated. However, we can learn already a lot from this simple exercise. It has the advantage of better controlling reliability of the results of the dynamical model since it can be compared with other studies made previously. It would be more difficult to disentangle the role of the different excitations in a collision involving two heavy ions and to be sure that the predictions made by the model are reliable.

Finally we have investigated another kind of excitation which corresponds to a geometrical perturbation of the system. It arises when a bunch of nucleons are removed from the target by the projectile. This may be, for example, the case in a participant spectator picture in which a small projectile drills a hole into a big target. The system which is left is unstable and evolves in time. It is interesting to study if it might break up into several pieces and the conditions which are required for multifragmentation to take place.

3.1 Thermal excitation

The problem of hot nuclei is a subject of current interest. At low temperatures the nucleus emits light particles leading to residual nuclei. It has also some probability of fission but this is a slower process. As the temperature increases more and more particles are evaporated and intermediate mass fragments are produced with a non negligeable probability. Above a certain temperature, which is not sharply defined due to the small number of particles present in the system, the nucleus can be unstable with respect to multifragmentation. We have investigated the role of thermal excitation using initial nuclei prepared at different temperatures. This is done by sampling the momentum distribution of the nucleons using locally a finite temperature Fermi distribution. The volume of the nucleus is taken to be the same as the one of the ground state nucleus. This simulates a fast heating of a nucleus at constant volume. This configuration does not corresponds to the equilibrium configuration of the nucleus at this temperature (this latter is associated to a larger volume) and it expands due to the thermal pressure. If the expansion is large enough the nucleus may become unstable with respect to multifragmentation.

As we said in section 2 the transition to multifragmentation is smooth due to the small number of particles contained in the system. We define, by convention, the critical point where multifragmentation takes place as the one where the mass of the largest cluster is half the mass A_0 of the initial system. It should be stressed again that this transition does not occurs at this critical value but that there is a broad range of conditions around it where it takes place. For a given value of the temperature we proceed in the following way. We study, for each event, the mass of the largest cluster at the point where the expansion is the largest (in the case where the system oscillates). If this mass is smaller than $A_0/2$ we count this event a as multifragmentation and not otherwise. Averaged over several events, this allows us to define the probability of multifragmentation associated to this temperature. The results are shown in fig.11a. One observes that the transition occurs between 8 and 12 MeV. The critical temperature is $T_{cr} \approx 10$ MeV. This corresponds to a thermal excitation energy per nucleon of $(\varepsilon^*_T)_{cr} = 6$ MeV/u.

3.2 Compression

Heavy ion collisions can lead to a large amount of compression. Consequently, it is interesting to study the influence of this collective excitation on the disassembly of nuclei. This effect is expected, and this has been demonstrated by several calculations [7,11], to be more efficient to break up nuclei than a pure thermal excitation. The reason is that it is of collective nature and corresponds to the degree of freedom connected with the expansion of the nucleus. Consequently, the same amount of excitation in compression gives a larger expansion than in the case of thermal excitation. To quantitatively estimate this effect we have studied different nuclei with different initial volumes. The difference between the energy of this configuration and the one of the ground state gives the compressional energy.

The percentage of multifragmentation is defined as above and is plotted in fig.11b as a function of the excitation energy per nucleon ε^*_c. The transition from a residual

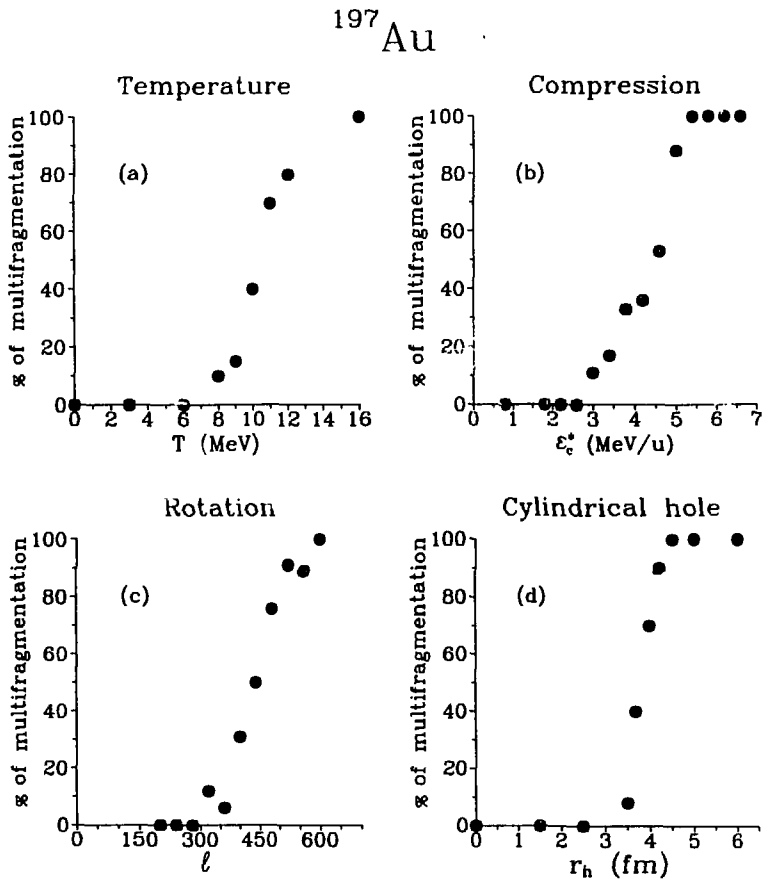

Figure 11: *percentage of multifragmentation, as defined in the text, for the* ^{197}Au *nucleus as a function of different values of the initial macroscopic parameter characterizing the excitation : (a) temperature T, (b) compression energy per nucleon* ε_c^**, (c) angular momentum* $\ell\hbar$ *and (d) radius of the cylinder* r_h*.*

nucleus to multifragmentation occurs between 3 and 5 MeV/u. The critical value is $(\epsilon_c^*)_{cr} \approx 4.5$ MeV/u. This is lower by 1 MeV/u than for the thermal excitation. This indicates that compression is more efficient to break up nuclei than thermal excitation.

3.3 Rotation

In heavy ion collisions at intermediate and high bombarding energies a lot of angular momentum can be brought into the system. It has certainly a great influence on the evolution of a nucleus. For this reason, it is interesting to apply our dynamical approach to a fast rotating nucleus and look if it is unstable with respect to multifragmentation on a small time scale. For low angular momentum values one knows that the nucleus should fission in two almost equal fragments but this is not the process we are interested in because it is much slower.

We suppose that the initial ^{197}Au nucleus has an angular momentum equal to $\ell\hbar$. We give, to each of the nucleons an angular velocity assuming that the nucleus is a rigid body. We look at the instabilities with respect to multifragmentation on a time scale which is at most a few hundreds fm/c. The percentage of multifragmentation is shown in fig.11c as a function of ℓ. One sees that the ^{197}Au nucleus is stable even at high values of the angular momentum and that large ℓ values are needed to induce multifragmentation. The transition occurs between $\ell \approx 300$-600 and one can deduce a critical value of $\ell_{cr} \approx 450$.

The instability by rotation in such a short time scale is different from the one corresponding to fission which needs much more time. For a ^{197}Au nucleus the limit of stability against fission takes place for $\ell \approx 80$. The result obtained here show that a nucleus is stable against rotation for much larger ℓ values. Since a lot of energy can be stored in the rotational motion, we conclude that rotation stabilizes more than it destabilizes nuclei with respect to multifragmentation. For $\ell = 450$, for example, the amount of energy tied up in rotation is ≈ 6.5 MeV/u.

3.4 Geometrical perturbation

We shall now study the case of a nucleus which has a cylindincal hole made by a smaller projectile in a head on collision. This system is excited and might be unstable with respect to multifragmentation. This instability depends upon the radius of the hole. Qualitatively one expects that a small hole does not destroy the nucleus while a big hole certainly breaks it up. We shall study such a situation as a function of the initial radius of the cylinder.

To construct the associated initial configuration, we remove all the nucleons from the ground state configuration which have their center inside the cylinder. Then we let the system evolve under the molecular dynamical equations. In fig.11d we show the percentage of multifragmentation as a function of r_h. It is calculated taking for A_0 the initial mass of the system after the projectile has drilled a hole in the center of the ^{197}Au nucleus. One observes a rather sharp transition occuring around $(r_h)_{cr} = 4$ fm. In a classical picture, a radius of 4 fm corresponds typically to a ^{40}Ar

or a ^{40}Ca nucleus. One may note that for $r_h = 4$ fm the mass of the residual nucleus is still $A_0 \approx 100$ (multifragmentation is supposed to occur, in this case, if the mass of the largest fragment is smaller than ≈ 50).

3.5 Spatial distribution of the clusters

Consider a nucleus which undergoes multifragmentation. It is interesting to know where the clusters are coming from. Since the low density configuration is obtained as the nucleus expands, one may think that the light clusters are emitted by the surface while the big ones are coming from the interior. This qualitative picture is supported by fig.12 which shows, for several events, the correlation existing between R, the distance between the center of mass of a cluster and the center of the nucleus, and and its atomic number. Heavy fragments are produced close to the center while lighter clustrers are coming from the surface.

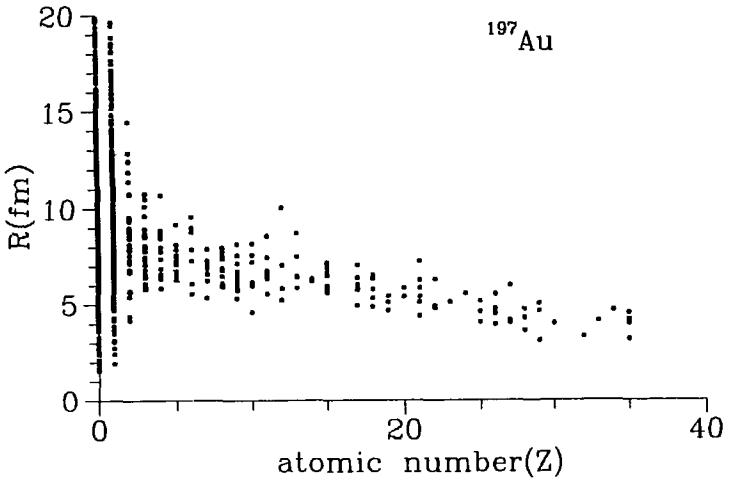

Figure 12: *correlation between R, the disiance between the center of mass of one cluster and the center of the initial nucleus, and its atomic number.*

4 Conclusion

We propose a simulation based on molecular dynamics and chromatic restructured aggregation to investigate the problem of nuclear multifragmentation. We have been especially carefull in checking that the model gives stable nuclei in the "ground state". We have applied the approach to the stability of ^{197}Au nuclei with different kind of excitation : heat, compression, rotation and a geometrical perturbation. In all cases one can induce multifragmentation if one deposits enough excitation energy. Compression turns out to be more efficient to disassemble nuclei than thermal excitation. Rotation does not play a crucial role concerning multifragmentation.

Finally, a hole drilled into ^{197}Au nucleus may induce multifragmentation if the mass of the projectile is greater than about 40 (^{40}Ar for example).

We are grateful to J.Aichelin for providing us with some of the subroutines of the molecular dynamical code.

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