On the break-up volume of nuclear multifragmentation

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ABSTRACT. Heavy-ion collisions at energies in the tens of MeV's often produce aggregates of nucleons of intermediate sizes. This fragmentation, which could be related to a phase transition, takes place early in the reaction when mass, energy, etc. can be shared between different chunks of matter. The region of space where the fragment-formation takes place, i.e. the "break-up" volume, is a parameter used by theories attempting to describe this phenomenon. In this work the transition-state theory is used to study this "break-up" volume.

RESUMEN. Las colisiones de iones pesados con energías del orden de decenas de MeV frecuentemente producen agregados de nucleones de tamaños intermedios. Esta fragmentación, que puede estar relacionada con una transición de fase, ocurre en etapas tempranas de la reacción cuando la masa, energía, etc. pueden ser compartidas entre diferentes cúmulos de materia. La región del espacio donde tiene lugar la fragmentación-formación, i.e. el volumen de "break-up", es un parámetro usado por las teorías que intentan describir este fenómeno. En este trabajo la teoría del estado transitorio se usa para estudiar este volumen de "break-up".

1. INTRODUCTION

During the last decade, nuclear physics has been strongly focused on the study of highly excited nuclear systems. In the energy region covered by, for instance, the MSU or TAMU cyclotrons the so-called nuclear fragmentation promises to help us understand the thermodynamics of hot and dense nuclear matter. At beam energies of several tens of MeV's per nucleon, reactions involving heavy-ions have been observed to decay into several fragments of masses smaller than the participant nuclei. This partition into intermediate masses could have a thermodynamical origin (resulting, for instance, from a phase transition or spinodal decomposition) and, thus, could help us understand nuclear matter at non-saturation densities and high temperatures. However, to make the connection between the observed fragments and the initial, and presumably, hot and dense system of nuclear matter, an accurate description of the breakup process is needed.

Since field theories (such as BUU, QMD, etc.) are incapable of describing fragmentation, this problem has been studied using statistical and other macroscopic models [1-6]. These calculations use an ensemble of mass partitions placing the fragments in thermal equilibrium in a "break-up" volume, and then determine the probability of specific mass-energy partitions by their statistical weight. These models, which reproduce several features of experimental data, are not entirely satisfactory. Besides excluding inter-fragment interactions, these models use an ad hoc freeze-out volume and other parameters. By correcting these problems, the transition state (TS) method of López and Randrup [4-6] represents a step forward in the right direction.
The TS method is based on a generalization of the transition state treatment commonly used for fission. Binary fission and nuclear fragmentation are both transitions from an excited compound system to one with a number of fragments formed. Considering the multifragmented system as a number of interacting fragments, it is possible to obtain its total potential energy as a function of a general disassembly radial coordinate. With this, the potential energy of the fragments will exhibit a barrier (i.e., a transition state) as the system goes from a compact configuration toward separated fragments. The partial width for the decay of the compound nucleus into a specified mass partition can then be calculated, in analogy to fission, with this potential barrier and the total excitation energy. Previously, the rate at which an excited nucleus breaks up into several fragments was derived [4], and the post-transition dynamics [5] was studied. And more recently, the pre-transition particle evaporation [6] was studied. In summary, the TS treatment reproduced the observed trend of increased fragment multiplicity for higher excitation energies, the after-breakup dynamics of the fragments was found to affect the original distributions of mass, energy and linear and angular momentum, the effect of the pre-transition particle evaporation on the potential barrier was quantified.

In the present report, the breakup volume (a common input in competing models) will be characterized. A brief description of the TS model is presented in the next section followed by an outline of the calculations made to study the break-up volume. The results are presented at the end with the preliminary conclusions.

2. Transition state theory

Our present study is carried out within the framework of the transition-state theory developed in Ref. [4] and we therefore first review the necessary ingredients.

We consider an excited compound system characterized by its total nucleon number $A$ and its total energy $E$. The system can then be described as an assembly of $N$ distinct (but interacting) prefragments, with masses and positions denoted by $m_n$ and $r_n$, respectively. For purposes of describing the excited system we employ the rms size $q$ as a measure of the spatial size of the system. Near the barrier top, where the system can be approximated by $N$ spherical prefragments, we have

$$q^2 = \frac{1}{m_0} \sum_{n=1}^{N} m_n r_n^2,$$

where $m_0 = \sum_n m_n$ is the sum of the prefragment masses. As explained in Ref. [4], using this radial coordinate $q$ (and a suitable parametrization of the interfragment potential), the transition state approach can be generalized to the multi-fragment case by counting the number of elementary phase-space states that pass over the conditional barrier.

In order to formulate the transition-state approximation to the disassembly problem, one considers the outwards probability current, i.e. the number of elementary multifragment states that pass by a given value $q = q'$ per unit time, $\nu$. The partial width for the
system to pass over the conditional barrier can then be written as

$$\Gamma_{A_1A_2...A_N}(E) = \frac{\hbar \nu_{A_1A_2...A_N}(E)}{\rho(A, E)}$$

where $$\rho(A, E)$$ is the total level density of the system, and $$\epsilon$$ and $$\epsilon_1...N$$ denote the internal energy, and the total excitation energy of the system when positioned at the barrier, and $$\tau_1...N$$ is the corresponding temperature. [The total excitation energy, $$\epsilon$$, refers to the total energy per nucleon, $$E/A$$.] The quantities in the bracket should be evaluated at the transition point (where the current $$\nu$$ has its minimum) and then averaged over all fragment positions $${\{r_n\}}$$ describing multifragment configurations that have been constrained to have a fixed center-of-mass position and an overall rms extension. The corresponding microcanonical sampling of fragment positions is easily done by means of the method described in Ref. [7].

3. THE BREAK-UP VOLUME

The TS method introduces, in a natural way, the transition state, i.e. the point where the flux of elementary multifragment states reaches a minimum. After that point, the system passes the maximum of the potential barrier and enters a state of “no return”. The transition state point, a natural result of the TS method, can serve to define what other theories have dubbed as the “break-up” or “freeze-out” volumes. In this introductory study we explore the size of the transition state as a function of mass partition and excitation energy.

The dependence of the transition state on the mass distribution and the excitation energy is clear from the two previous equations, but to quantify this dependence a microcanonical sampling must be performed. In order to do this we use the TS method to simulate the disassembly of an excited system with mass of 120 and excitation energies ranging from 2 to 6 MeV/A. The mass partitions selected correspond to decays into symmetric mass splits of multiplicity 3, 4, 5 and 6 (i.e. three fragments of mass 40, four of mass 30, five of mass 24 and six of mass 20). For each of these cases, a large number of breakup events were performed to fully explore the fragment configuration space.

The generalized coordinate $$q$$ was obtained as in Eq. (1) and the transition width $$\Gamma$$ as in Eq. (2). For each event, a transition state was obtained with its corresponding radial size $$\bar{q}_i$$ and decay width $$\Gamma_i$$. The average location of the transition state, $${\bar{q}}$$, which corresponds to the generalized radius of the break-up volume, was then obtained through

$$\bar{q} = \frac{\sum_i q_i \Gamma_i}{\sum_i \Gamma_i}$$

The uncertainties were also calculated using the usual expression for standard deviation (i.e. $$\sigma = \sqrt{q^2 - \bar{q}^2}$$). The next section shows some preliminary results of this calculations.
4. Results

The results for the decay of $A_0 = 120 \rightarrow 30 + 30 + 30 + 30$ are shown in Fig. 1. The normalized width was calculated using the expression $\Gamma' = \Gamma_i/\sum \Gamma_j$. The bin used to group the values of $q$ was 0.9 fm and the number of events was over 3000. It can be seen that the value of the generalized radial coordinate $q$ falls roughly in the range of 5 to 9 fm, somewhat independent of excitation energy. The same calculations were performed for different mass partitions and all showed a rather similar behavior.

It is also interesting to explore the connection between $q$ and the mass partition. The values of $q$ for all mass partitions at $\epsilon = 4$ MeV/A are shown in Fig. 2. The values of $q$ get bigger as the number of fragments increases, showing a small, but significant, dependence on the mass partition. To further investigate these results, the average value for $q$ was calculated for several mass partitions at all energies. Fig. 3 shows the results of this calculation and again we see that the values of $q$ get bigger for larger multiplicities. $\sigma$ varied for different multiplicities being about 0.4 for multiplicity 3 at $\epsilon = 2$ MeV/A and increasing up to 2.0 for multiplicity 6 at $\epsilon = 6$ MeV/A.

All the results obtained are in good agreement with the values used by Bondorf and coworkers [1], which range around 6 fm when averaged over all possible multiplicities. Due to the different approximation used, Friedman's model [3] gives an equivalent radii between 9 and 12 fm for the expanded volume where the fragments are produced. In the future, a more comprehensive study of this comparison to other models will be carried out in more detail.

5. Summary

In previous works [4–6] the transition state treatment of nuclear fragmentation was developed and applied to the calculation of multifragment breakup widths, to describe the complicated dynamical evolution the fragments undergo after passing over the conditional barrier, and to explore the loss of matter before the system reaches the transition state. The present study investigates the location of the transition state, e.g. the break-up volume, and its dependence of excitation energy and fragment multiplicity.

The average radius of the break-up volume, $\bar{q}$ was found to range in the 5 to 9 fm. A small dependence on excitation energy was observed, and a relatively stronger dependence on fragment multiplicity was found. These findings are in general agreement with the values of the break-up volume radii used by other fragmentation models [1], and are somewhat smaller than those predicted by the expansion-evaporation model of Ref. [3].

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FIGURE 1. Distribution of $q$ for different excitation energies. For a source with initially $A = 120$ nucleons and decaying into $30 + 30 + 30 + 30$, the dependence of the value of the generalized radial coordinate $q$ is shown as a function of the excitation energy per nucleon of the decaying system. The numbers next to the curves denote the excitation energy per nucleon in MeV’s. The normalized width was calculated as explained in the text.

FIGURE 2. Distribution of $q$ for different mass partitions. For a source with initially 120 nucleons and an excitation energy of $\epsilon = 4$ MeV per nucleon, the distribution of the values of $q$ is shown for different mass partitions.
FIGURE 3. Energy dependence of $\bar{q}$. For a source with initially 120 nucleons decaying into several multiplicities, the dependence of $\bar{q}$ is presented as a function of excitation energy. The numbers on the curves denote the fragment multiplicity.

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