Conf-9105144--2

UCRL-JC--106927

DE91 012034

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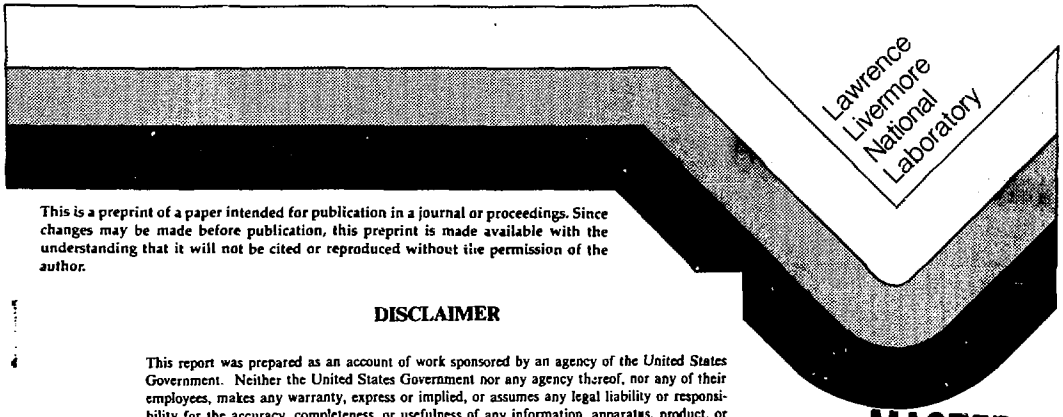
This paper was prepared for presentation at:
The 7th Adriatic International Conference on Nuclear Physics
Heavy-Ion Physics--Today and Tomorrow,
May 27-June 1, 1991
Islands of Brioni, Croatia, Yugoslavia

April 1, 1991



SDI: Statistical Dynamic Interactions*

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Abstract

We focus on the combined statistical and dynamical aspects of heavy ion induced reactions. The overall picture is illustrated by considering the reaction $^{36}Ar + ^{238}U$ at a projectile energy of 35 MeV/Nucleon. We illustrate the time dependent bound excitation energy due to the fusion/relaxation dynamics as calculated with the Boltzmann master equation. An estimate of the mass charge and excitation of an equilibrated nucleus surviving the fast (dynamic) fusion-relaxation process is used as input into an evaporation calculation which includes 20 heavy fragment exit channels. The distribution of excitations between residue and clusters is explicitly calculated, as is the further deexcitation of clusters to bound nuclei. These results are compared with the exclusive cluster multiplicity measurements of Kim *et al.*[1], and are found to give excellent agreement. We consider also an equilibrated residue system at 25% lower initial excitation, which gives an unsatisfactory exclusive multiplicity distribution. This illustrates that exclusive fragment multiplicity may provide a thermometer for system excitation. This analysis of data involves successive binary decay with no compressional effects nor phase transitions.

Several examples of primary versus final (stable) cluster decay probabilities for an A=100 nucleus at excitations of 100 to 800 MeV are presented. From these results a large change in multifragmentation patterns may be understood as a simple phase space consequence, invoking neither phase transitions, nor equation of state information. These results are used to illustrate physical quantities which are ambiguous to deduce from experimental fragment measurements.

1. Introduction

Excitation of nuclei to high energies involves first a dynamic, fast process, followed by statistical deexcitation of residues surviving the fast processes.

Interpretation of experimental results requires an understanding at the theoretical level of the relative importance and interplay of the fast dynamic and of the slower statistical interactions.

These mechanisms are quite familiar to us, dating from the early intranuclear cascade model and the Weisskopf evaporation theory, and their offspring. It is desireable to understand the consequences and expectations of these approaches, and their abilities to interpret experimental results, before invoking models involving much more sophisticated ideas, e.g. phase transitions and compressed matter. This may provide a familiar baseline against which we may search for unexpected results. In the present work we illustrate analysis of the reaction of ^{36}Ar on ^{238}U at 35 MeV/nucleon incident energy. Kim *et al.* have measured the exclusive multifragmentation for this system.[1] We illustrate the interplay between the fast fusion/relaxation time for this reaction, and the multifragmentation, assuming that the latter results from a successive binary evaporation process of the relaxed system. We see the degree to which, if the interpretation is valid, the exclusive multifragmentation pattern may be used as a thermometer for the equilibrated nucleus following the dynamically determined fusion-relaxation process. We will also see if this very simple interpretation is adequate to reproduce the experimental result, a necessary but not sufficient requirement for it to be a valid interpretation of the experiments.

2.0 Calculations

2.1 Fast emission processes

The use of the BME in treating precompound decay in heavy ion reactions, and in estimating the equilibrated excitation has been adequately discussed in the literature; we refer to these papers for details of the present calculations.[5] The BME has been shown to give an excellent agreement with experimental high energy neutron and proton emission spectra, without parameter variation. However, precompound decay also includes nucleons with energies which are similar to those emitted from equilibrated systems; the differentiation at these emitted neutron energies is ambiguous.[6] Therefore, estimates of the energy removed in precompound processes has, at present, a subjective aspect. We will use a value based on the excitation when the obvious fast emission processes have ceased, bearing in mind that complete thermalization may come at a somewhat later time, and therefore at lower internal excitation.

In Fig. 1 we show the BME results for excitation vs. time for the residue formed when 35 MeV/nucleon ^{36}Ar is incident on ^{238}U. The calculation is performed for time increments of 2×10^{-23} sec. At the extreme left, we see the excitation resulting from the first nucleon interactions during the coalescence (fusion) process. The BME calculates the energy loss due to the emission of nucleons as well as the excitation brought in by the coalescing nuclei. Fusion is complete (in the constant velocity assumption used) at $\approx 1.4 \times 10^{-22}$ sec.; the maximum excitation (800 MeV) occurs at 1.2×10^{-22} sec. If a compound nucleus had been instantly formed, the internal excitation ($E_{cm}+Q$) would have been 970 MeV; this value is indicated by the horizontal line in Fig. 1. The difference in these energies illustrates the point that the full excitation is never available due to the dynamical nature of the formation and relaxation processes.

Subjective analyses of the time derivatives of the calculated neutron emission rates leads to an estimate of equilibration after $\approx 3 \times 10^{-22}$ sec., at which time the internal excitation is $\approx$ 720 MeV, and on average 9 neutrons and 2 protons have been emitted. We initially use this estimate to give the starting point for the statistical emission process.

An inference from some experiments is that the collective fission process may have time delays of 10^{-20}-10^{-19} sec.[7] Perhaps then, heavy fragment emission should also be delayed with respect to nucleon emission by a period less than that for fission? This is an interesting open question . We will consider the residual nucleus at 10^{-21} sec (at which time the internal excitation is $\approx$550 MeV) to illustrate the sensitivity of calculated multifragmentation yields to the initial excitation of the equilibrated nucleus; the excitation may be seen (Fig. 1) to be related to any time delay for fragment decay since the residual post-fusion excitation energy decreases monotonically with time.

2.2 Statistical Calculations

Two new codes were derived from the W-E type ALICE nuclear reactions code.[4,8] The first permitted the emission of up to 20 ejectiles in addition to n, p and α particles, with explicit folding over all possible energy partitions between light and heavy fragments for fragments of A>4. Additionally, the exclusive multiplicity of emitted fragments may be followed. The second code version accepts the excited fragments up to Z=20, A=48 from the first code and follows the de-excitation of these fragments to particle bound residues. Greater detail on these codes may be found elsewhere. [4,8]

Our goal at present is to investigate whether or not such a statistical-dynamic approach provides a satisfactory interpretation of the data, and if so, the sensitivity of the results to the excitation (temperature) of the equilibrated system. We have not attempted to use all the 'best possible' components in our calculations; to do so would delay results for a very long period. We have used a Fermi gas level density, without fitting to known low lying levels of light ejectiles. We do, however, extrapolate the single particle level density parameter based on the work of Toké-Swiatecki to allow for surface effects.[9] Limits on level densities due to restrictions to bound nucleon levels should also be considered,[10,11] but are not incorporated in the present work. The parabolic barrier model of the ALICE code was used to generate inverse cross sections for clusters; the parameters of this routine had been selected to give a reasonable reproduction of experimentally measured heavy ion fusion excitation functions (the optical model was used for neutron and proton inverse cross sections).[12,13] A more precise calculation would result from using a very careful empirical parameterization of the experimental fusion excitation function data, with particular attention to the near and sub-barrier regions,[13] which are very important to the evaporation process.

Preliminary calculations were performed for 60 light cluster ejectiles; the 20 most abundant isotopes were selected for use in the calculations to be presented. These are compared with experimental measurements of Kim *et al.* in Fig. 2. The ejectiles treated were ^{9}Be, ^{10}Be, ^{11}B, ^{12}C,^{14}C, ^{15}N,^{16}O, ^{18}O, ^{21}F, ^{22} Ne, ^{23}Ne, ^{27}Mg, ^{28}Mg, ^{30}Si, ^{31}Si, ^{32}Si, ^{36}S, ^{37}S, ^{42}Ar, and ^{43}Ar.

The MSU[1] group made measurements of multifragmentation with several `gates'. In Fig. 2 we show the experimental results for multiplicities which were gated on fission fragments at an angle of 133^{o}, i.e. reasonably central collisions. The solid angle was reported as ≈80% of 4π; additionally there were kinematic cutoffs for the detectors.We have taken the liberty of adjusting the data reported by Kim *et al.* by $1/(0.80)^{m}$, where m is multiplicity (reported for fragments of $Z \geq 4$) as a solid angle correction. There is no correction for the counter kinematic cutoffs, so data points corrected for cutoffs would lie higher than those shown in Fig. 2. This correction should be greater the higher the multiplicity, since the fragment kinetic energies will decrease with increasing multiplicity. This means an increasing fraction of the ejectile spectrum would lie below the low energy detector cutoffs. The experimental data of Fig. 2 therefore represent lower limits.

We assume the nucleus $^{263}_{108}$X equilibrated, following the fast cascade, with ≈720 MeV of excitation. The primary emission multiplicities (before the excited

clusters undergo further multiple binary decay) are shown in Fig. 2, by the open squares. They underestimate the zero multiplicity yield, and overestimate all others. However, the experiment measures the final particle bound clusters. Calculated bound cluster multiplicities are shown by closed squares, which for clarity have been joined by a smooth line; these results are in reasonable agreement with the experimental data, which are lower limits. The sensitivity of the calculation to excitation energy may be illustrated by assuming that cluster emission is delayed until 10^{-21} sec after initiation of the reaction (this being a completely arbitrary time). At this time, the average nucleus is $^{263}_{108}$X at 550 MeV of excitation. For this case we show only the multiplicities of the primary fragments (triangles) before post emission de-excitation. These results are in reasonable agreement with experimental data for multiplicities up to two; beyond that they underestimate the data, remembering that the data points will increase due to kinematic cutoffs, while the calculated values will decrease due to further binary de-excitation. In particular we note that the calculated result for multiplicity five is quite low. This discrepancy will increase when the corrections to data and calculated results have been made. This illustrates that the exclusive multiplicity measurements are sensitive to the excitation of the equilibrated nucleus, to the extent that the assumed mechanism is valid.

In Fig. 3 we show some detail of the calculation of the de-excitation of primary fragments. The fractional yields for the first ejectiles from $^{263}_{108}$X are shown as closed points, summed over mass number for each atomic number considered. The histogram represents the calculated particle bound yields. It is clear from Fig. 3 that most clusters observed under similar circumstances result from the sequential decay of a heavier cluster. Therefore, the high energy region of the cluster spectrum is not likely to yield information on the temperature of the emitting nucleus, nor is the low energy region likely to be indicative of the coulomb barrier of the parent. These comments are based on the considerable 'kinematic kick' which the light ejectiles receive during the deexcitation process.

In addition to the Ar+U system described above, we have asked the question "What are the fragment yield distributions when nuclei are initially equilibrated at some arbitrary excitation?" For $^{100}_{44}$Ru nuclei at excitations of 100 to 800 MeV, we considered the evaporation of 100 clusters between ^{5}Li and ^{48}Ca, plus n, p and alpha particles. In Fig. 4 we show the primary yields versus excitation for emission from compound nuclei and averaged over the evaporation cascade. It may be seen that above ≈400 MeV, cluster emission has a high probability so that after the emission of one cluster there is sufficient

excitation and high probability to emit a second cluster, etc. There is a significant change in the multifragment pattern, above 400 MeV due to the phase space of successive binary decay.

In Fig. 5 we show the yield of ^{48}Ca from $^{100}_{44}Ru$ at 400 MeV of excitation (and from the daughters of the evaporation cascade) and the final yields when the primary ^{48}Ca fragments deexcite to bound final products. It may be seen that the properties of the final (measured) clusters will not be characteristic of the emitting system.

4.0 Conclusions

We have provided one possible interpretation of the exclusive multiplicity measurements of Kim *et al.* as a fast dynamic reaction during which ≈25% of the excitation is removed by precompound neutron and proton emission, followed by the heavy residue de-exciting by successive equilibrium binary decay. For this calculation, it was important to consider the partition of available excitation between heavy and light fragments, and the binary decay of the primary ejectiles to give bound clusters as are observed in experimental measurement. The agreement is over 5 orders of magnitude with no attempt having been made to adjust parameters in the calculation.

Comparisons of calculations each with the same approximations (level densities, inverse cross sections) at two different initial excitation energies, shows that the exclusive multiplicity measurement is sensitive to excitation energy of the equilibrated nucleus. More quantitative deduction of the excitation will require better input into the model calculations, and experiments performed with detectors having low kinematic cutoffs for cluster detection, and near 4π acceptance angles. The interpretation we have presented is perhaps the simplest possible in terms of previously investigated reaction mechanisms. It will be interesting to see which alternative mechanisms[14] will provide equally good interpretations of data of the type considered, and then to see what experimental measurements might be used to select the better models to pursue in each regime of target-projectile mass and energy.

Acknowledgement

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48. One of the authors (MB) appreciates partial support from Alexander von Humboldt Foundation and Frankfurt Univ. during the performance of this work.

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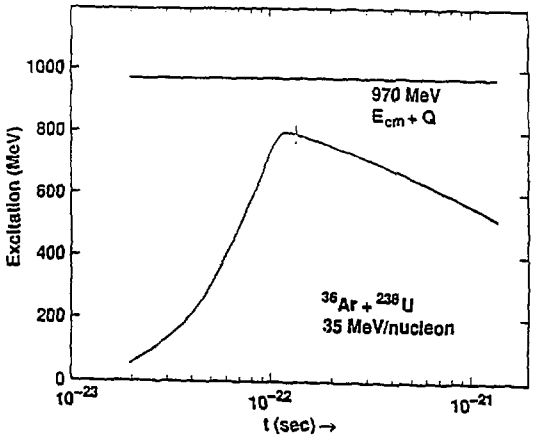

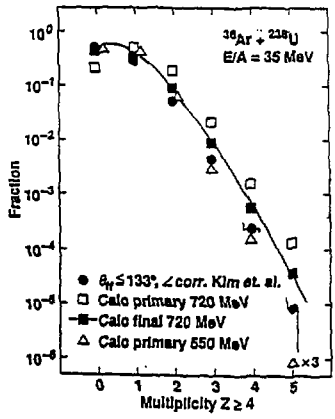

Fig. 1.

Excitation vs. time for the reaction $^{36}Ar + ^{238}U$ at 35 MeV/nucleon as calculated with the Boltzmann master equation. The reaction begins at $2x10^{-23}$ sec. (the time step used in the calculation). The excitation is shown on the ordinate, time on the abscissa. Fusion is complete at $1.4X10^{-22}$ sec., indicated on the excitation vs. time curve by a short horizontal line slightly beyond the maximum excitation. The horizontal line at 970 MeV represents the excitation available in the center of mass (i.e. if a compound nucleus were instantaneously formed).

Fig. 2

Calculated and measured multiplicities for the $^{36}Ar+^{238}U$ system. The ordinate gives the fraction of reactions for which zero to five fragments of $Z \geq 4$ were observed. In the case of experimental data, the measurements were gated on fission fragments with an opening angle $\leq 133^{0}$. There is no such gate on calculated results. The experimental data of Kim et al. were adjusted to 4π solid angle as described in the text. The open squares represent calculated primary yield results for 720 MeV of excitation; the solid squares joined by a smooth curve are the results for bound final fragments. The open triangles represent calculated primary yields when the initial excitation is assumed to be 550 MeV.

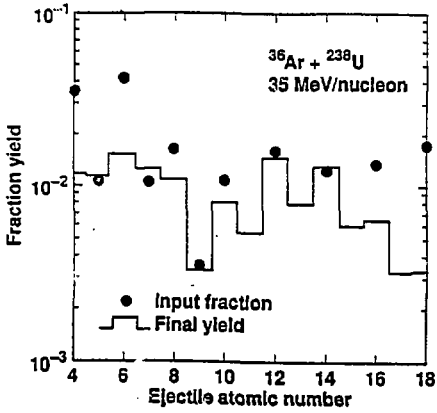

Fig. 3
Initial and final yields for primary fragments emitted from a compound nucleus at 720 MeV. The closed circles represent the primary fractional yields for the first ejectiles (multiplicity one or more). The histogram represents the yields after the ejectiles have de-excited to particle bound nuclei.

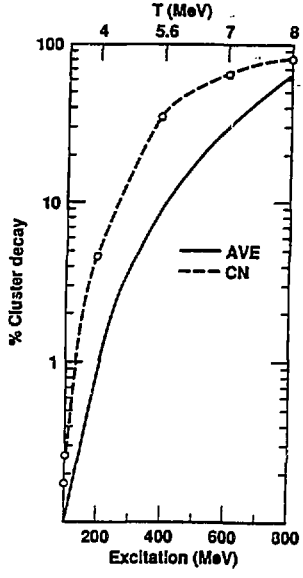

Fig. 4
Calculated primary cluster yields versus compound nucleus excitation for $^{100}_{44}$Ru nuclei (dashed line) and averaged over the evaporation cascade (solid line).

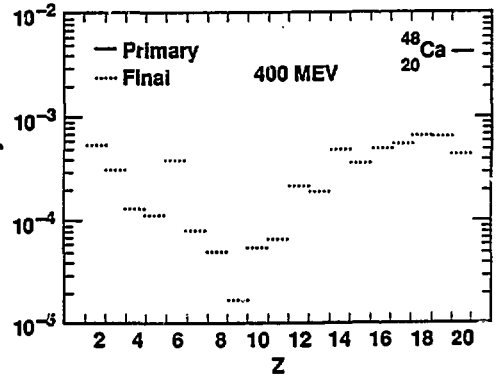

Fig. 5
Primary and stable yields from ^{48}Ca clusters emitted from $^{100}_{44}$Ru nuclei at 400 MeV of excitation.