Dynamics of heavy-ion fusion probed by *d*/*p* double ratios from a cross bombardment

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(Received 20 May 1994; revised manuscript received 21 June 1995)

The particle decay ensuing from the reactions 86.0 MeV ^{16}O + ^{148}Sm and 239.1 MeV ^{64}Ni + ^{100}Mo was studied. These reactions each form ^{164}Yb compound nuclei excited to ≈ 54 MeV. Particle decay from compound nucleus producing reactions was selected by gating on the gamma-ray fold and the angular region of the particle emission. While there are no discernable differences in the dominant decay channels between the two reactions, there are fewer deuterons from the more symmetric system. This difference can be interpreted two ways: as a suppression of the emission of energetically expensive clusters during the time required for shape equilibration (which is predicted to be longer for the more symmetric entrance channel), or as an enhancement of the emission of energetically expensive clusters from the more asymmetric system at the very early stage of the collision when the initial energy deposited is only available to a reduced number of nucleons. The first explanation is identical to that used in recent high energy photon work while the second could be identified as the result of the emission of clusters on the multistep compound branch leading to the fusion of the low energy heavy ions. If the first explanation is adopted, the observed suppression is larger than predicted by a standard statistical decay model coupled to a dynamical fusion model, but consistent with work using high energy photons as a probe of fusion dynamics.

PACS number(s): 25.70.Jj, 24.60.Dr, 25.70.Gh

I. INTRODUCTION

The amalgamation of two heavy nuclei into one mononuclear shape and ultimately to a compound nucleus is a complex process. Excitation energy will be generated in the nascent compound nucleus as the radial energy is dissipated, as the charge to mass ratio is equilibrated, and as the surface area is reduced. Studies of deeply inelastic reactions imply that these subprocesses do not evolve on identical time scales [1]. The damping of the radial energy and the equilibration of the charge to mass (leading to deposition of part of the reaction Q value) are thought to occur quickly, in ≈0.1 zs (1 zs $=1\times10^{-21}$ s). The remainder of the macroscopic Q value, arising from the reduction of surface area, is thought to take an extended time (several to many zs) to be deposited. Moreover, and a central issue for the present work, this slower energy deposition process is predicted to depend on the total mass and the entrance channel mass asymmetry or more accurately the location of the entrance channel with respect to the Businaro-Gallone peaks in the potential energy surface.

In the present work we address the question of how the deposition of energy into the nascent compound system, from processes with different time constants, can affect the decay of the excited system. Recent work by Thoennessen *et al.* [2] addresses one aspect of this question; namely, can one observe the effects of a long shape equilibration time due to the commensurately slow accumulation of thermal energy? Thoennessen *et al.* [2] used high energy photon emission as a probe of this process. In order to avoid having to draw conclusions by comparing to the absolute yields of statistical models, it is necessary to compare two systems in a cross bombardment [3]. The work cited above [2] does this as do we in the present work. The fundamental difference between this and the previous work is that we utilize charged particle emission yields rather than photon yields. Furthermore, to reduce systematic errors, we compare ratios, most notably d/p, between the cross bombardment reactions. Therefore it is double ratios which constitute our primary observable.

While one might think that our (as well as all other) observable would primarily be sensitive to differences (between entrance channel conditions) in the development of the slowest degree of freedom (shape), this may not be the case. The significant success of the multistep compound picture of compound nucleus formation [4] obligates us to consider the possible effect of the very early dynamics (during the ≈0.1 zs when the radial energy is being dissipated and the charge/mass partition between the fragments is being equilibrated) when the deposited energy would be dispensed to a subset of the nucleons.

In the present work we present the d/p double ratio as an observable sensitive to the overall fusion dynamics. If we confine our analysis of the fusion process to the consideration of the evolution of the slower shape degree of freedom, our results suggest that this degree of freedom equilibrates slower than predicted by fusion models. This is the same conclusion that was reached by the previous work [2].

Unfortunately, a more global consideration of the fusion process suggests that it is conceivable that both our and other observables are also sensitive to the very early dynamics. Unfortunately, no tractable self-consistent calculation can be done to model this very early dynamics. Therefore, while the present work adds evidence that observables sensitive to the dynamics of heavy ion fusion exist, we cannot at this time make definitive statements about the sensitivities of these observables to specific features of the dynamics.

II. EXPECTATIONS BASED ON FUSION + EVAPORATION MODEL CALCULATIONS

The time dependences of the thermal energy and surface area, predicted by a fusion dynamics model HICOL [5], for

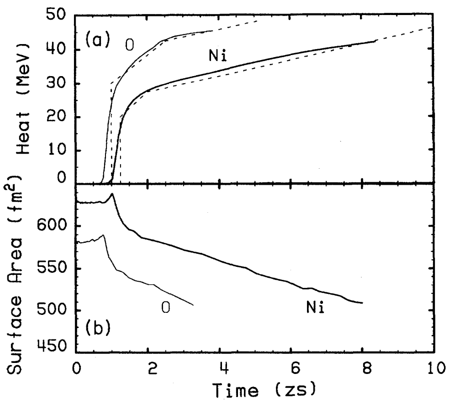

FIG. 1. Predicted heat (a) and surface area (b) as a function of time, for two systems ^{16}O + ^{148}Sm (thin lines) and ^{64}Ni + ^{100}Mo (thick lines) each with $25\hbar$. These calculations were performed with HICOL [5]. The dashed lines are three segment approximations to the HICOL results which are used in calculations to model the formation and decay of these reaction systems (see text and Fig. 2).

the two entrance channel mass symmetries studied in the present work are shown in Fig. 1. The more symmetric system is predicted to require an additional 6 zs to reach a compact mononuclear shape. We call the time interval, during which the system's surface area is larger than that of the final equilibrium shape, the fusion time. The surface energy, being proportional to the surface area, is large during this time and thus as long as the deposited energy is statistically distributed throughout the entire system, this system will be relatively cold. Therefore, if the system emits anything, the emissions will have to be energetically inexpensive ("cheap"). This leads to an inversion of the standard logic, which would predict that "expensive" emissions come out first. In short, the longer a system spends in a region of low excitation energy, the stronger will be the suppression of "expensive" emissions. Since ultimately all decay sequences must remove the same amount of energy and since "cheap" emissions (primarily neutrons, but protons and α particles can also be considered in this category) remove almost all the available energy, these more prevalent emissions would exhibit only slight differences in the integrated emission probabilities (multiplicities) between the two systems.

On the crudest level, the expectation for the suppression (for a given decay step) is given by

$$\frac{(\Gamma_{\rm exp}/\Gamma_{\rm chp})_{\rm sym}}{(\Gamma_{\rm exp}/\Gamma_{\rm chp})_{\rm asy}} \approx \frac{\exp(-[\mathrm{cost}_{\rm exp}-\mathrm{cost}_{\rm chp}]/T_{\rm sym})}{\exp(-[\mathrm{cost}_{\rm exp}-\mathrm{cost}_{\rm chp}]/T_{\rm asy})} . \quad (1)$$

The subscripts "exp" and "chp" stand for expensive and cheap, respectively, and the "cost" for particle emission is the sum of the separation energy and the mean channel kinetic energy. A suppression is generated and enhanced by large differences in the statistical temperatures ($T_{\rm sym}$ and $T_{\rm asy}$) and by large differences in the costs. The time dependence of the former difference is the desired physics. The latter difference is of the order of 3 MeV for giant dipole resonance (GDR) γ rays (as compared to either neutrons or protons), 7 MeV for deuterons, and 9 MeV for tritons. In Ref. [2] the suppression of high energy γ rays (in the GDR region, $\approx$ 15 MeV) in the symmetric system, as compared to the asymmetric system, was used as the indicator of the extended fusion time. As mentioned before, in the present work we utilize d/p and, secondarily, d/α multiplicity ratios.

To quantify our expectations, we have modeled the formation and decay of the nuclear system using a continuous heating and evaporation model [6]. The alternative consistent approach (discrete particle transfers leading to heating and discrete evaporative emissions) is an extremely difficult problem, well beyond the scope of the present work. We further assume that there is only one object responsible for emitting fragments. Initially (see end of this section) we assume that this object is composed of the entire 164 nucleons which can be assigned one excitation energy and spin. This is appropriate for times after the initial loss of radial energy [nearly vertical lines in Fig. 1(a)] where the nuclear profile is predicted to be a deformed object without a highly constricted neck.

This model then gives the time derivative of the multiplicity (m_i) of an evaporated particle i as

$$\frac{dm_i}{dt} = \frac{\Gamma_i(Z,A,E^*)}{\hbar} , \quad (2)$$

with the time derivative of the excitation energy given by

$$\frac{dE^*}{dt} = -\sum_i \frac{dm_i}{dt}[B_i+\epsilon] + \frac{dQ}{dt} . \quad (3)$$

In the above, B_i is the binding energy, ϵ is the average channel kinetic energy, and dQ/dt is the heating rate. In our simulation of the formation and decay we have not used the direct results of the heating rate from HICOL [5], but rather we have parametrized the direct results in terms of several regions of constant dQ/dt. Aside from the simplicity of this approach it allows us to easily assure that each simulation has exactly the correct deposited energy. The constant sections of dQ/dt are shown as dashed lines in Fig. 1.

In our calculations any time dependence of particle penetrabilities has been neglected. On the other hand, we have modeled several evolutions of the level density constant a. Most notably we have considered the dependence of a on surface area. Application of the results of [7] to the fusion time would suggest that a should be increased due to larger surface area. However, as will be seen, to reproduce the experimental data, decreased values of a are needed during the fusion time. Motivated by the data we have done calculations where a is a constant but small value during the fusion time, after which it is allowed to evolve to the more reasonable value of $A/9$.

The results for a typical calculation of the sort described above are shown in Fig. 2(a) for ^{16}O- and ^{64}Ni- induced reactions forming the same Yb compound system, which ultimately is excited to 54 MeV (above the nonrotating ground state). The particle fluxes (in particles/zs) are shown for n, p, α, d, and t (top to bottom) as smooth curves. The integrated multiplicities (divided by 100) are shown as squares (open for the ^{16}O system and solid for the ^{64}Ni system). Several things should be noticed: (a) All early emissions are suppressed in the ^{64}Ni system. (b) The ^{64}Ni system ulti-

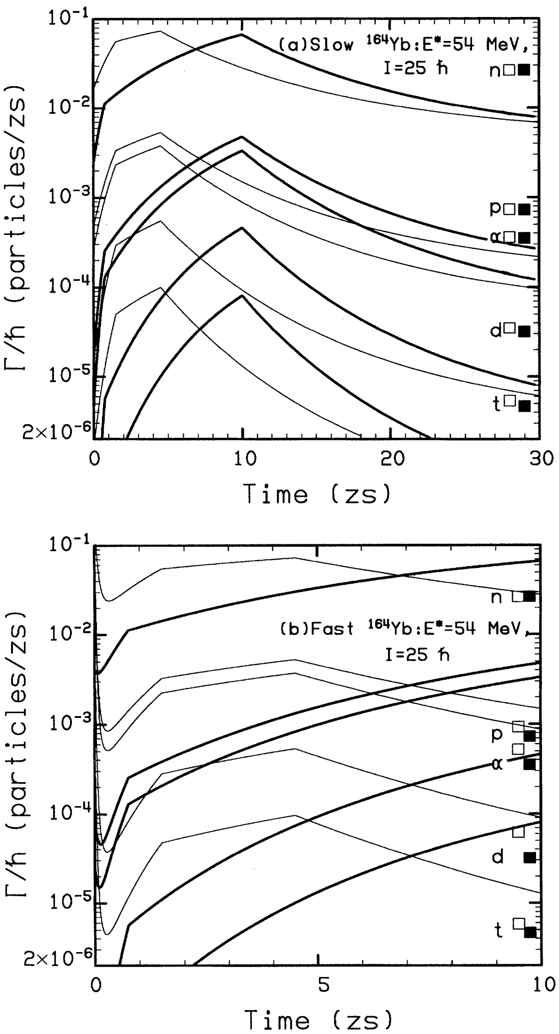

FIG. 2. Emission rates of n, p, α, d, and t as a function of time. As in Fig. 1 the thin lines are for the ^{16}O, while the thick lines are for the ^{64}Ni induced reactions. In this calculation the level density constant is $a=A/15$ during the heating and it relaxes back to $a=A/9$ with a time constant 10 zs after the heating is complete. The initial spin is $25\hbar$. The total particle multiplicities (divided by 100) are shown on the right hand side as open squares for the ^{16}O + ^{148}Sm system and as solid squares for the ^{64}Ni + ^{100}Mo system. These calculations ultimately produce a compound system with 54 MeV of excitation energy as measured from the nonrotating ground state. The cusps in the emission rates are the result of the of the parametrization of the continuous heating rate [shown in Fig. 1(a)] by the three line segments. The difference between (a) and (b) is that in (a) the entire system is the statistical source while in (b) the source starts out to be one with twice the size of the projectile which then grows into one containing all the remaining nucleons with a time constant of 0.1 zs. The time scale in (b) has been expanded to emphasize the early times. The calculations in (a) and (b) are indistinguishable after 1 zs.

mately catches and passes the ^{16}O system in excitation energy and in emission rate. (c) In the end, the multiplicities of n's, p's, and α's are almost identical for the two systems. (In fact there are slightly more n's from the symmetric system.) (d) The effect of the extended sequestering of energy in the surface for the Ni reaction can be observed, as expected, as a reduction in the yield of the more expensive particles (d and t). However, the predicted effect is small, amounting (in this calculation) to 8.5% for d's and 14.6% for t's. Such a weak effect would be impossible to measure with absolute yields and demands that ratios of yields (and thus double ratios because systems are being compared) be employed to reduce or eliminate many of the sources of systematic errors.

This type of calculation is adequate to model the slower (>1zs) shape equilibration component of the fusion dynamics. In fact this represents an improvement over the previous work [2] which did not consider continuous heating, but rather treated the heating process stepwise. However, this logic is inadequate for the treatment of the initial stages of the fusion process. What is needed here is a multistep compound calculation for heavy ion fusion which considers cluster production. Presently this is an intractable problem. We therefore resort to a schematic calculation intended only to address the question of whether or not these very early dynamics could affect our observable.

For this purpose we make a small but important change in the logic described above. We consider the initial energy deposition (the rapid rise in the heating curve seen in Fig. 1) to result in an excited subsystem consisting of twice the number of nucleons as are contained in the projectile. As the system continues to heat up, the number of participant nucleons grows to the full number contained in the compound nucleus. The $1/e$ time for the growth in the number of participants is taken to be quite fast, 0.1 zs, a value close to the mean time required for a nucleon to traverse a nucleus. This logic is similar to the "hot spot" envisioned at higher energies. The primary difference is that here it is unreasonable to require geometric proximity.

Figure 2(b) displays results using this revised logic. The particle fluxes are identical to those shown in Fig. 2(a) except for times less than (1 zs). During these very early times there is a rapid upswing in the particle fluxes for the ^{16}O + ^{148}Sm system. While the differences may appear slight they have a substantial affect on the integrated multiplicities, which now display much larger differences between the systems. (The t emission has not been enhanced by as much as d emission has, because at these very early times the deposited energy only marginally exceeds the t separation energy.)

The results of both types of calculations, performed with different values of the level density constant a and different prescriptions for the time development of a, are presented and compared with the experimental results in the Sec. IV of this paper.

III. DATA AND ANALYSIS

The data used in the present analysis were collected at the Holifield Heavy-Ion Research facility at ORNL. The details of the experiment and the bulk of the experimental analysis have been published [8]. The present work extends the previous analysis to include the weak deuteron exit channels. The experiments were performed using the Dwarf Ball particle detection system [9] positioned inside of the Spin Spectrometer [10]. The Dwarf Ball detected charged particles and can separate p's and d's above 5 MeV (see Fig. 11 of [9]).

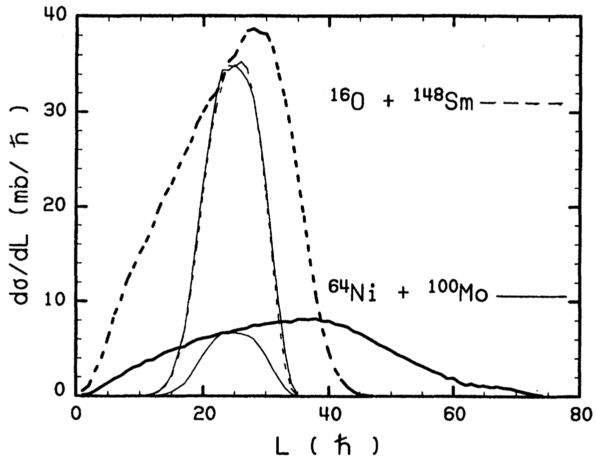

FIG. 3. Calculated total fusion spin distributions for ^{16}O + ^{148}Sm (thick dashed lines) and ^{64}Ni + ^{100}Mo (thick solid lines) along with the calculated portions of these distributions selected with the k_γ gate employed (thin dashed and solid lines.) Two versions of the selected spin distribution for the ^{64}Ni + ^{100}Mo system are shown (thin solid lines). The ordinate scale is appropriate for the lower one and the upper one has been normalized to the area of the selected ^{16}O + ^{148}Sm spin distribution for comparison.

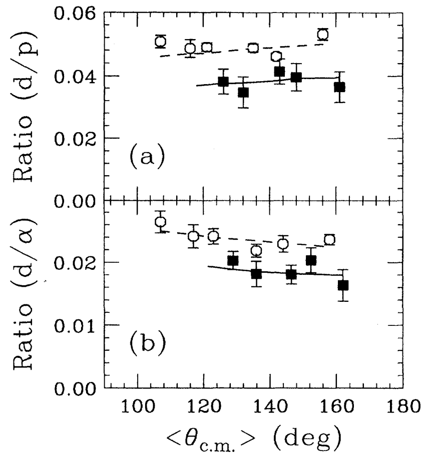

FIG. 4. Angular distributions of d/p and d/α ratios from the two reaction systems. The open and solid symbols give the d/p and d/α ratios for the ^{16}O + ^{148}Sm and ^{64}Ni + ^{100}Mo reactions, respectively. The lines are fits of simulations to the data. The data points are plotted at the average of the two centroids of the c.m. angular distributions. The angular distributions for each particle type are quite wide; however, the centroids of these distributions for the two particles (in each ratio) differ by only a few degrees.

The Spin Spectrometer provided the ability to gate on a γ-ray fold (k_γ), thus allowing the selection of the spin distribution. A detail, relevant to the present analysis, is that the excitation energies for the two systems were not exactly matched. The cross-section-averaged excitation energies were 54.4 and 53.4 for the ^{16}O- and ^{64}Ni-induced reactions, respectively.

The presence of light element impurities in the target presents a major difficulty in the present analysis. Reactions on these impurities are easily removed from the data set with the ^{16}O beam because these reactions produce k_γ distributions which do not extend significantly above values of 10. The same is not true of the ^{64}Ni reaction. Therefore, in order to obtain reliable estimates of the particle multiplicity ratios, data must be selected by placing gates on particle energy and angle, as well as on k_γ. The energy and k_γ gates employed were: $E_p^{\text{c.m.}} \geq 10$ MeV, $E_d^{\text{c.m.}} \geq 9$ MeV, $E_\alpha^{\text{c.m.}} \geq 14$ MeV, and $12 \leq k_\gamma \leq 17$.

Simulations with EVAP [11] and experimentally verified response functions [10] indicate that this k_γ gate selects nearly identical spin distributions. This is shown in Fig. 3 which displays the predicted initial total spin distributions contributing to fusion (thick lines) and the portion of these distributions selected with the γ-ray fold gate employed (thin lines). (A coupled channels calculation is used for the ^{64}Ni + ^{100}Mo system. Such calculations have been shown to reproduce the fusion excitation function and the k_γ distribution [8].)

Figure 4 shows the d/p and d/α ratios from both systems. These points are averages of the data from the four or five detectors in each ring of the Dwarf Ball and are plotted at the centroid of the distribution of angles covered by each ring. These distributions are $\approx 20°$ wide [full width at half maximum (FWHM)]; see the discussion below and the figure caption.

To investigate whether the differences seen in the ratios shown in Fig. 4 could arise from the instrumental response, Monte Carlo simulations were preformed. EVAP, coupled to a software detector filter, was used to generate p, d, and α particles with energy spectra and angular distributions consistent with the data [12]. An initial run of the simulation determined, for each particle type and system, the angular distribution within each detector. A second run of the simulation determined if a detector was hit and, if so, transformed back to the center of mass frame using an angle randomly taken from the distribution determined from the initial run of the simulation. The treatment of the experimental data was also subjected the same randomization procedure.

The simulations of the ratios for the two systems are indistinguishable in shape and magnitude (this is not shown). The lines in Fig. 4 show the results of the simulation scaled to fit the data. The angular dependence of the data is well described by the simulations for the backward angular region, indicating that these data are not contaminated with components from reactions on target impurities or deeply inelastic reactions (see below). The scaling yields percent suppressions (symmetric/asymmetric) of 23 ± 4, 19 ± 4, and 2.6 ± 1.6 for the ratios d/p, d/α, and α/p, respectively (see Table I). In addition to these results, we also analyzed the d/α data from a slightly lower k_γ gate, $9 \leq k_\gamma \leq 15$. This case yielded a suppression similar to that given above.

Since the excitation energies of the two systems were not exactly matched, we have corrected the above suppressions using the results from EVAP. In these calculations the spin distribution corresponding to the k_γ gate was used and the excitation energies were taken to be the cross-section-weighted energies over the target thickness. The corrected values are given in parentheses in Table I.

The statistically significant differences in the experimental d/p and d/α ratios imply that either the entrance channel mass asymmetry affects the decay process or that in this

TABLE I. Calculated and measured suppressions of the deuteron yield for the symmetric ^{64}Ni + ^{100}Mo relative to the asymmetric ^{16}O + ^{148}Sm fusion. The values without parentheses were calculated or measured at the excitation energies used in the experiment. The calculated values at the same excitation energy for the two systems are given in parentheses. The experimental values corrected to correspond to 54.4 MeV, in both systems, are also given in parentheses.

Relative yield suppression	Model (slow) $A/8$	$A/10$	$A/12$	$A/15$	Experiment	Model (fast) $A/8$	$A/10$
$\left(1-\frac{(d/p)_{Ni}}{(d/p)_O}\right)\times 100$	5.4 (0.7)	7.0 (1.9)	9.1 (3.4)	13.5 (8.5)	23.0 ± 4.0 (18.0 ± 4.0)	11.0 (5.5)	26.0 (18.0)
$\left(1-\frac{(d/\alpha)_{Ni}}{(d/\alpha)_O}\right)\times 100$	5.1 (0.4)	5.5 (1.5)	7.2 (3.2)	10.8 (7.1)	19.0 ± 4.0 (14.0 ± 4.0)	8.1 (3.6)	18 (12.0)
$\left(1-\frac{(\alpha/p)_{Ni}}{(\alpha/p)_O}\right)\times 100$	2.0 (0.2)	1.4 (0.4)	1.7 (0.6)	2.4 (1.2)	2.6 ± 1.6 (1.6 ± 1.6)	2.7 (1.9)	6.7 (5.7)

experiment we have not selected true fusion events which form residues. At issue here are the possible contribution from fusion-fission and deeply inelastic scattering events. This issue was addressed (and dismissed) in [2]; however, it is of sufficient importance to warrant further discussion.

We first consider the ^{64}Ni + ^{100}Mo system. EVAP calculations and recent experiments on a similar system [13] indicate that the fission cross section is no more than 1/11th of the residue cross section. On the other hand, the strongly damped cross section may be as large as the residue cross section. The total energy available for excitation of both fragments is only 30 MeV in the fusion-fission case and 33 MeV in the strongly damped case. These numbers come from the Viola systematics [14], but have been verified by experiments on a similar system [13]. Calculated proton multiplicities for a fission fragment (with half the mass, half the energy, and $5\hbar$) and a projectilelike fragment (with half the energy and $5\hbar$) are 1/50th and 1/450th of that for the compound system. In addition to the meager excitation energies, the relative neutron excesses, as compared to the compound system, are responsible for these small numbers. While these factors alone would suggest that the present data set (which require a charged particle, a proton being by far the most likely) is negligibly affected by these reactions, an argument can be made for why the contributions should be even smaller than the estimates provided above. The lower boundary of the k_γ gate is 12 units. This implies that, in the binary scenarios mentioned above, each fragment on the average must have at least $10\hbar$. At such spins the proton multiplicities are expected to be reduced an additional factor of $\sim$ 10 relative to the estimates obtained using $5\hbar$.

For the ^{16}O + ^{148}Sm system, the primary concern is the possibility of an enhanced d yield due to the sequential breakup of an excited light projectilelike fragment. While this process can contribute to the overall charged particle yield at forward angles, it should not contribute to the charged particle yield at backward angles. Because of the very small breakup energy from the decay of an excited light deep inelastic fragment ($Z\sim 8$), the sequentially emitted fragments should be strongly focused about the direction of the projectilelike fragment. As a result, it is impossible for d emitted from a projectile deflected near the classical grazing angle to be detected in the most backward three rings of the Dwarf Ball (most backward three points in Fig. 3). It is therefore not surprising that the angular distribution of the ratio of particle yields (shown in Fig. 4) is independent of angle at large angles in agreement with the expectation for pure compound nucleus emission. Two additional arguments can be made as to why breakup of projectilelike fragments is unlikely to contaminate our data. The the emission of d's, even from such a light system, is unlikely. The kinetic energy loss, corresponding to complete damping at the entrance channel asymmetry, is only 29 MeV. Because of either unfavorable reaction Q values or large d separation energies, the projectilelike fragment would have to receive more than 1/2 the total available excitation energy to emit a deuteron. (If the damping was not complete, there would be less total energy and the focusing argument made above would be even more restrictive.) Furthermore, as mentioned above, such reactions will not transfer enough spin to populate the k_γ fold region we have selected for analysis (see Fig. 3).

IV. DISCUSSION

This discussion is divided into two sections. First, we will assume that the entire observed effect originates from the sequestering of energy in an extended surface. We can then ask, under what conditions can we explain the observed effect? We will then turn to question the initial assumption.

Results from calculations which presume that all the dissipated energy is available for statistical emission from a system initially consisting of the total number of nucleons (initially $A=164$) are given to the left of the data in Table I. This table presents results as a function of the value of a utilized during the fusion time. In each of these calculations the value of a is relaxed to a value of $A/9$ (after the fusion time), which is a resonable value for moderately excited nuclei, with a time constant of 10 zs. (Actually these *ratios* do not change significantly if the level density constants are maintained at the value used during the fusion time throughout the entire decay process.) As would be expected, smaller values of a increase the magnitude of the predicted suppression due to the increase in the overall decay width and thus the probability that some decay occurs during the fusion time. However, even extremely small values of a do not reproduce the observed double ratios.

We have also performed calculations in which the level density evolves with shape as prescribed by [7]. While varying in time, the average level density constant is near $a = A/9$, and therefore the calculated suppressions are similar to the results obtained for $a = A/9$. We have also investigated the sensitivity of these results to mismatches in the spin distributions. If the average spin of the ^{64}Ni + ^{100}Mo system was $1\hbar$ higher, we would expect only a 5% suppression (rather than 1.9%; see Table I) for $a = A/10$. A mismatch of more than this is unlikely (a $1\hbar$ mismatch would accommodate a substantial tail, which we do not think exists; see Fig. 3). More to the point, since the observed effect is close to 20%, any explanation based primarily on an angular momentum mismatch can be eliminated.

If we restricted ourselves to this explanation of the observed effect (temporary sequestration of energy in the extended surface) we can ask, how long would the fusion time have to be in order to reproduce the observed double ratios? If the level density constant is taken as $a = A/10$, the fusion time for the ^{64}Ni + ^{100}Mo system would then have to be stretched to $\sim$40 zs to reproduce the observed suppressions. This time is $\sim$ 4 times longer than that based on Ref. [5]. However, these data can be reproduced with fusion times only extended a factor of 2 if very small values of a are employed (see also [15]).

These findings prompted us to ask another question. Might it be that the apparent requirement of an exceedingly small level density constant implies that the relevant system, during some or all of the fusion process is substantially smaller than the entire (ultimate) compound system? In order to investigate this effect, we performed calculations with a emission source which evolves from one containing twice the number of nucleons in the projectile to one containing the total number in the combined system (minus the nucleons which have been lost in the mean time.) This evolution is very fast and makes miniscule changes in the major evaporation channels. This logic is inspired by the preequilibrium exciton model or, more fundamentally, the multistep compound model; however, here the evaporation during this very early time is purely statistical and thus clusters can be ejected.

The results from these calculations are shown to the right of the experimental results in Table I. Here we see that magnitude of the observed ratios can be reproduced with reasonable level density constants. With this perspective, one would consider the experimental data as exhibiting an *enhancement* of emission from the more asymmetric system. While this calculation is primitive (in that the initial heating and participant number are not coupled) and the results quantitatively suspect, its success in reproducing the data argues that it must be considered as possibly part of the explanation of the observables that we and others have proposed as probes of the dynamics of fusion.

In summary, we have observed d/p, and d/α emission ratios which are smaller for the more symmetric of two entrance channels in a cross bombardment. It is considered unlikely that these differences are the result of the detector response, mismatched spin distributions, or the admixture of non-fusion-evaporation events. These ratios are consistent in the respect that they decrease in magnitude as the difference in the cost of the particles decreases (compare the ratios for d/p, d/α, and α/p).

This suppression can be interpreted, as was a similar signal in previous work, as evidence for a longer fusion time for the symmetric entrance channel. We point out that such an entrance channel effect is far more subtle than those reported previously and which have been proven erroneous [8,16]. If one makes the interpretation that this effect is due to the difference in the shape equilibration time between the two entrance channels, then in order to reproduce the present data the fusion time must be a few to several times longer than predicted by the HICOL model [5]. However, it is also possible that our observable (and we see no reason to exclude the one previously used—high energy photons) is sensitive to the earliest phase of the fusion dynamics where the excited system contains a reduced number of participants.

ACKNOWLEDGMENTS

This work was supported by the Director, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under Contracts Nos. DE-FG02-87ER40316 and DE-FG02-88ER40406.

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