Clustered and neutron-rich low density ''neck'' region produced in heavy-ion collisions

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The creation of a clustered and neutron-rich midvelocity (''neck'' or ''hot spot'') region in intermediate-energy heavy-ion collisions is discussed. Reaction simulations suggest that the preponderance of the neutron-rich species in isotopic and isobaric ratios results primarily from the amplification of the initial neutron excess due to d (and by inference α-particle) cluster formation. [S0556-2813(97)01604-X]

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Recently we presented both isotopic and isobaric ratios for light clusters produced in the four (cross) bombardments: 55 MeV nucleon ^{124,136}Xe+ ^{112,124}Sn [1]. In the past, we also presented hydrogen isotope ratios for another system [2]. All of these data indicate a strong enrichment in the yield of neutron-rich fragments as the cluster rapidity approaches the center-of-mass value (we call this midvelocity), in comparison to the fragments found in the projectile (and in one case target) rapidity region(s). We will stress here that this work concerns the bulk of the reaction cross section, when the impact parameter is at least one nuclear radius. A possible connection of the enrichment cited above to the neutron-rich species seen in low energy ternary fission [3] and to the surface composition predicted by both macroscopic and microscopic theories has been mentioned [1]. Yet a specific underlying mechanism(s) responsible for the enhancement of the neutron-rich species in the midvelocity region has not been established.

The possible explanations fall into one of two general categories involving either (1) the density (and possibly temperature) dependence of the nuclear symmetry energy or (2) the tendency for nuclear material to cluster into small symmetric clusters (d's and α particles predominately). Both the kinetic and potential parts of the nuclear symmetry energy increase with density. The kinetic part increases as $\rho^{2/3}$. While the specific density dependence of the potential part is uncertain (between $\rho^{1/2}$ to ρ^2, depending on the model [4]) this part also increases with density. As the projectilelike and targetlike fragments reseparate a low density ''neck'' region may be formed in between. If isospin equilibration were sufficiently fast, there might be a net neutron flux into the low density central region due to (1) the density dependence of the symmetry energy. Complicating the argument and possible reaction scenario given above is the temperature dependence of the symmetry energy. The temperature dependence of the symmetry energy is uncertain for temperatures of only a few MeV (temperature scale relevant to changes in the energy-dependent effective mass m_ω) [5,6], but at higher temperatures the symmetry energy should decrease.

The other possibility, (2) clustering, is a well-documented theoretical expectation for low density nuclear matter [7–10]. To explain the experimental observations, the reaction scenario must involve substantial survival (not simply production) of small symmetric clusters from the intermediate velocity region. Since the midvelocity or overlap region in heavy-ion collisions initially contains a neutron excess, the clustering amplifies this excess and thus the central region evolves toward a mixture of small clusters in a neutron-rich gas. Some fraction of those clusters (or clusters traversing this region from the other sources) can serve as nucleation sites which can coalescence with the free nucleons in the gas, producing neutron-rich heavier fragments. This scenario requires that the midvelocity region be to a large extent *decoupled* from the bulk of the nearly symmetric matter residing in the target and projectile and therefore requires no, or little, isospin equilibration. The dynamical reaction simulations presented in this work indicate that the second of the two mentioned scenarios is more relevant to the intermediate energy reactions under study.

Figure 1 presents reaction simulations which result from solving the Boltzmann-Uehling-Uhlenbeck (BUU) equation [11,12] for an impact parameter $b=8.8$ collision of ^{136}Xe and ^{124}Sn at 55 MeV nucleon; one of the reactions studied in Ref. [1]. Of relevance for the present study, the experimental isospin-dependent cross sections are used as well as an isospin-dependent mean field. The Pauli blocking of collisions is treated in an isospin-asymmetric fashion and the degrees of freedom for small clusters $A=2$ and 3 are explicitly considered. Note that α particles are not considered; see below. The treatment of clusters [12] uses explicit transport equations with both production and absorption terms. Cooper pairs, rather than true d's, are suppressed in the calculation by only allowing d's to form only if the nucleon occupation, averaged over a phase space volume approximately equal to that of the d-wave function, is less than 0.3.

The projections of the total, neutron, and proton densities are shown in Fig. 1. The projections for neutrons and protons *exclude* the nucleons bound in the small clusters treated explicitly in the code. The last column of Fig. 1 displays the n/p ratios $R_{n/p}$, both excluding (solid symbols) and including (open symbols) the nucleons bound in small clusters, plotted as a function of D, the projection of the space coordinates on the separation axis. ($D=0$ corresponds to the center of mass position.) The overall asymmetry (ignoring

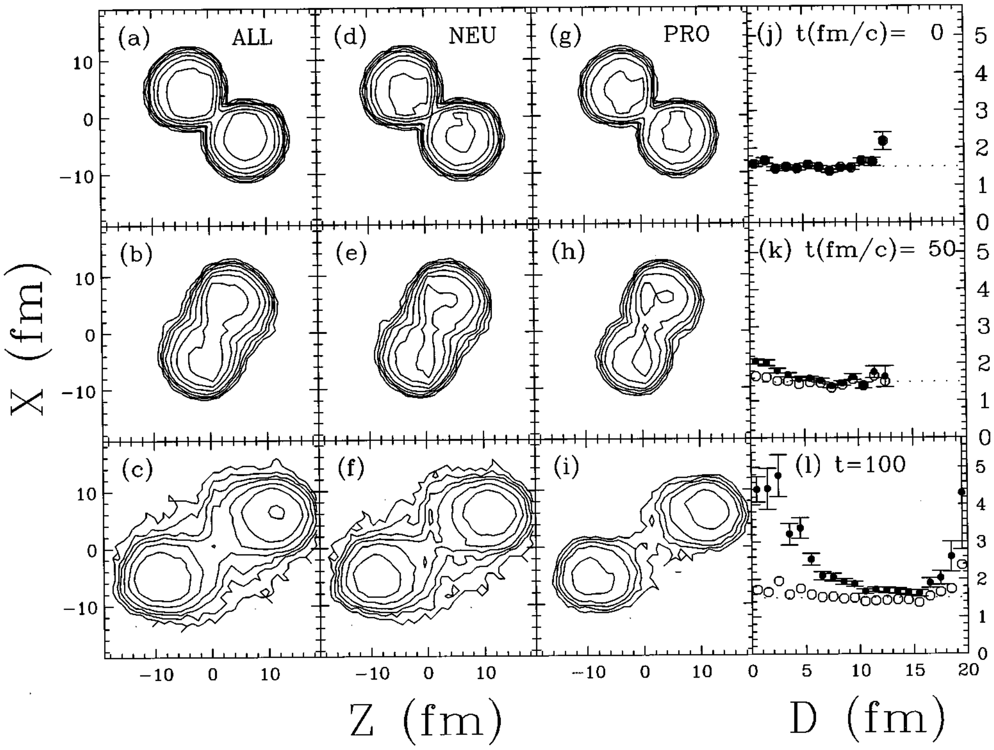

FIG. 1. Boltzmann-Uehling-Uhlenbeck simulation of a collision between ^{132}Xe and ^{124}Xe at 55 MeV nucleon and an impact parameter of 8.8 fm. The different panels show projections [in the plane defined by the projectile momentum (Z axis) and the impact parameter (X axis)] of the total (a),(b),(c), neutron (d),(e),(f), and proton (g),(h),(i) densities. The nucleons bound in light clusters are *excluded* from the contour plots (d)–(i). Sections (j)–(l) display the neutron-to-proton ratio $R_{n/p}$ as a function of the magnitude D of the projection of the space coordinates on the projectile-target separation axis, excluding (solid circles) and including (open circles) the nucleons bound in small clusters. ($D=0$ corresponds to the center of mass position.)

whether the nucleons are in clusters or not, open circles) grows slightly with time in the central region [also see Fig. 2(a)] and, further, is maintained on the exterior surface. While this equilibration process is expected, from the arguments given at the beginning of this Brief Report, and studied fully in the thermodynamic (uncharged) limit by Müller and Serot [13], it is marginal compared to the amplification of the free n/p ratios due to cluster formation (closed points).

Calculations performed for larger (smaller) impact parameters generate the same general effect seen above but with larger (smaller) asymmetries of the central region involving fewer (more) nucleons. The first of these trends is shown in Fig. 2(a). Here we show the free (solid lines) and total (dashed lines) values for $R_{n/p}$ for the central region as a function of time, for impact parameters of 6.8, 8.8, and 11.9 fm. The amplification (due to the clustering) of the free n/p ratio over the slightly enriched total n/p ratios is roughly a factor of 3. The number of nucleons in the central region varies from 35–40 (for $b=6.8$ fm) to ≈ 4 (for $b=11.9$ fm). In the latter case the number of nucleons is so small that large clusters cannot be constructed from nucleons from this region alone [14].

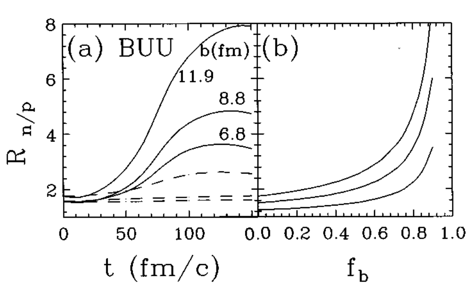

FIG. 2. (a) Free (solid lines) and total (dashed lines) $R_{n/p}$ ratios for the central region as a function of time for collisions at $b=11.9$, 8.8, and 6.8 fm. The ratios increase with b (the uppermost solid and dashed curves are for $b=11.9$ fm). (b) The free n/p ratios as a function of the charge fraction bound in symmetric clusters for total n/p ratios of 1.25, 1.50, and 1.75.

The simple relationship between the bound charge fraction (in symmetric clusters) and the free n/p ratio is shown in Fig. 2(b) for three different total asymmetries. For the system studied in the present work the overall system has a n/p ratio of 1.50 (middle line). However, the simulations suggest that the material in the midvelocity region can have a higher overall n/p ratio closer to 1.75 (upper line), due to equilibration, when the density has dropped well below saturation [for the impact parameters exceeding one radius; see Fig. 2(a), dashed lines]. The experimental data suggest that roughly 50% of the charge in the midvelocity region is bound in α particles. As this is a lower bound for the bound charge fraction, the results of this work indicate that one should expect isotopic/isobaric ratios, which favor the neutron-rich species, far in excess of the coalescence expectation using the overall n/p ratio. However, due to the omission of α-particle clustering, the observed sensitivity of the extent of clustering to the Pauli blocking (isospin separate or averaged), and the known difficulties of treating the clustering+blocking problem accurately [15,16] the results presented here cannot be considered as quantitative expectations.

In summary, reaction simulations suggest that the influence of the equilibration process (on the total asymmetry of the central region) is small compared to the effect of clustering (d's in the BUU code and α particles in reality), on the asymmetry of free nucleons. This work suggests that the explanation of the preponderance of neutron-rich isotopes observed in experiments is primarily the result of the coalescence of a small fraction of the clusters with a neutron-rich gas in the midvelocity region. Needless to say, the sequential decay of these fragments and the intermixing of the emissions from the other sources are relevant to a complete description of the isotopic and isobaric ratios.

While this result could have been anticipated from the results of charge equilibration studies [1,17,18], on the one hand, and the special role played by deuterons and α particles in nuclear matter calculations of the free energy as a function of density, on the other, it has been overlooked in the discussions of observable transitions in intermediate heavy-ion reactions. We suspect this is due to the fact that the process is nonequilibrium, involves a small fraction of the nucleons in the total reaction, and is best characterized in peripheral collisions.

It is intriguing that the scenario presented here is similar to a phase in the early evolution of our universe, with the difference that the relative abundances of n's and p's are reversed.

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