Isospin dependent multifragmentation in ^{112}Sn+ ^{112}Sn and ^{124}Sn+ ^{124}Sn collisions

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Significant differences in the relationships between fragment, neutron, and charged particle multiplicities were found between ^{112}Sn+ ^{112}Sn and ^{124}Sn+ ^{124}Sn collisions at 40 MeV/*A*. In this paper we explore the possibility to explain this phenomenon in the framework of percolation models, and find that the results are only reproducible in part. [S0556-2813(97)06805-2]

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Percolation models have proven highly successful in the simulation of multifragmentation reactions in the past [1,2]. Within these models, fragmentation is described by first distributing a set of points or sites, each representing a nucleon, on a three-dimensional lattice, which represents the bonds between the sites. In the case of a simple rectangular lattice, each site is connected to six nearest neighbors, however, it has been shown that the model is to a large degree independent of the lattice structure [1,3]. In the second step, some lattice bonds are randomly broken with a probability that in nonisospin dependent percolation models is the only free parameter. The remaining connected clusters are identified with the fragments of the reaction, the bond-breaking probability with the excitation energy per nucleon [4].

In this work, the percolation model of Bauer *et al.* [1] is modified by the explicit inclusion of isospin degrees of freedom, i.e., the lattice is comprised of protons and neutrons instead of just nucleons.

The question in this paper is whether the isospin dependence found in the comparison between experimental multifragmentation data of ^{112}Sn+ ^{112}Sn and ^{124}Sn+ ^{124}Sn collisions [5] can be reproduced within the framework of percolation simulations. Again, we especially focus on the average number of intermediate mass fragments (IMF's, $3 \leqslant Z \leqslant 20$) versus the number of charged particles (Fig. 1, left panels) $\langle N_{\mathrm{IMF}} \rangle (N_c)$ and the number of neutrons (Fig. 1, right panels) $\langle N_{\mathrm{IMF}} \rangle (N_n)$. The full circles denote the experimental results for the ^{124}Sn+ ^{124}Sn reaction, the open circles the results for the ^{112}Sn+ ^{112}Sn reaction. The striking feature about these distributions is the ''splitting'' of $\langle N_{\mathrm{IMF}} \rangle (N_c)$, and the position of the maxima in $\langle N_{\mathrm{IMF}} \rangle (N_n)$. Both do not agree with common multifragmentation models, in which the distributions $\langle N_{\mathrm{IMF}} \rangle (N_c)$ should lie on top of each other, and the positions of the maxima in $\langle N_{\mathrm{IMF}} \rangle (N_n)$ should simply correspond to the ratio of neutron abundances in the respective isotopes.

For each simulated collision event, first the impact parameter is randomly selected. Then with a simple Monte Carlo integration, the number of protons and neutrons in the overlap zone of the two nuclei is determined. We employ an approximation in which the nucleons outside the overlap zone are neglected — we found this approximation to be appropriate by studying Boltzmann-Uehling-Uhlenbeck (BUU) simulations [6] of the collisions at different impact parameters, which clearly showed distinct spectator regions in the final state even for small impact parameters. The nucleons in the overlap zone are randomly distributed on a rectangular lattice.

The lattice bonds are then broken with a probability p, which we determined in two different ways: in one method we set it equal to a parameter p_0 which we obtain by fitting to the experimental data [5], in the second method we choose p according to a Gauss distribution around p_0, i.e., for each simulation, p varies slightly in order to simulate excitation energy fluctuations. A comparison between both methods showed no significant difference in the outcome except for better statistics in the latter method for higher event multiplicities as large bond-breaking probabilities were included. Since we find the inclusion of excitation energy fluctuations to be more realistic, we settled for the latter method.

We then identify clusters of nucleons which are still connected with each other. However, since those clusters are not necessarily a stable configuration of protons and neutrons, we experimented with several different algorithms to achieve fragment stability. Methods included a redistribution of protons and neutrons between the fragments, further fission of the fragments, evaporation of protons and neutrons from the fragments, and simulations with no additional stability criteria applied. Also, the definition of stability is not obvious: the experimental lifetime data applies to nuclei in their ground state and is not directly transferable to the fragments of a multifragmentation reaction. Since we found the outcome to only be slightly dependent on the definition used, we settled on a stability criterion where the fragments are required to have a ground-state lifetime that is long enough for them to reach the detectors. Fragment stability is then achieved through fission and evaporation mechanisms. As an unfortunate side effect of these mechanisms, the relationship between the bond breaking probability p_0 and the excitation energy is not obvious anymore, rather the combination of the initial bond-breaking and further mechanisms leads to an effective bond-breaking probability that is higher than p_0 — therefore, p_0 sets a lower limit for the excitation energy.

Of the order of $10^6 - 10^7$ events were simulated for each setup; for each individual event the number of charged particles, neutrons, and IMF's was recorded, where, in accordance with the experimental data, we employed detector efficiencies of 0.9 for all charged particles and 0.65 for neutrons.

The code was first applied to the experimental results of Ref. [7]. Figure 2 shows the the average number of interme-

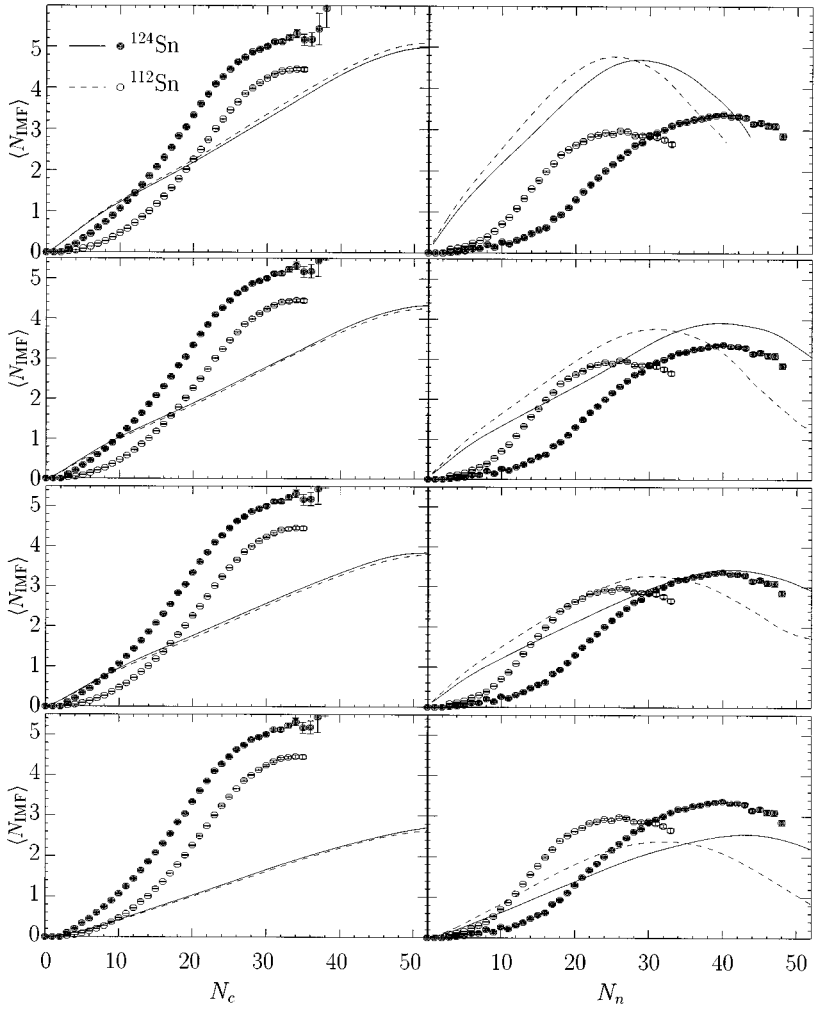

FIG. 1. Average number of intermediate mass fragments (IMF's) versus number of charged particles (left panels) and neutrons (right panels). The full circles denote the experimental results [5] for a ^{124}Sn+^{124}Sn collision, the open circles the results for a ^{112}Sn+^{112}Sn collision, both at 40 MeV/*A*. The solid lines represent percolation simulation results for the heavier isotopes, the dashed lines for the lighter ones. The top row was calculated without any stability mechanism, in the second row an evaporation mechanism is employed, in the third row a fission mechanism, and the fourth row was achieved with a combination of both.

diate mass fragments ($3 \leqslant Z \leqslant 20$) versus the number of charged particles [$\langle N_{\mathrm{IMF}}\rangle(N_c)$] for ^{197}Au+^{197}Au collisions. The experimental results in the left panel refer to different energies per nucleon [7], the curves in the right panel to percolation simulations at different bond-breaking probabilities p_0. It had been found earlier [8] that percolation codes generally slightly underpredict the number of intermediate mass fragments, which was attributed to the possible existence of noncompact decay geometries. Overall, however, the model was found to reproduce the data reasonably well.

In the next step, we address the question of the reproducablility of the isospin dependence found in Ref. [5]. The top row of Fig. 1 shows the result of a simulation with a bond-breaking probability distribution centered around $p_0=0.7$ and a half-width of 0.1. In this simulation, no stability mechanism is applied. The solid line corresponds to the simulation for the heavier isotope (experimental data indicated by full circles), the dashed line to the lighter isotope (open circles). The difference between the isotopes in $\langle N_{\mathrm{IMF}}\rangle(N_c)$ could not be reproduced, the outcome basically reflects the trivial autocorrelation that every IMF is a charged particle, the slope is determined by the ratio of IMF's versus lighter fragments. The linear relationship will eventually break down in events with high multiplicities when more and more fragments are smaller than IMF's. The experimental data shows that for the neutron-rich system relatively fewer fragments with $Z<3$ are formed, a trend that cannot be seen in the simulation. A difference in $\langle N_{\mathrm{IMF}}\rangle(N_n)$ (right panel) is predicted, which, however, is not surprising: in the collision of the neutron-richer isotopes, more neutrons are emitted. The positions of the maxima, i.e., at 25 and 29 neutrons, respectively, correspond to the ratio of neutrons in the isotopes, 62 and 74, respectively ($25/29 \approx 0.86; 62/74 \approx 0.84$). In the experimental data the maxima are at 25 and 40 neutrons, the ratio of ≈ 0.63 is incompatible with the simple explanation above. At high neutron numbers, statistics get rather unsatisfactory, and we do not reproduce the high neutron multiplicities seen in the experiment for the heavy isotope. This disagreement between simulation and experiment led us to focus on the fragment stability as a possible reason for the isospin dependence: the initial fragments produced in the neutron-rich collision might have a ''healthier'' ratio of protons/neutrons, so that more initially formed IMF's end up in the detector.

The second row of Fig. 1 shows the outcome of a simulation with an evaporation mechanism to achieve fragment stability: protons and neutrons are broken off the fragments until the remainder is stable. In the simulation shown, in the case of $N>Z$, neutrons are broken off, and vice versa. In another simulation, protons and neutrons had been broken

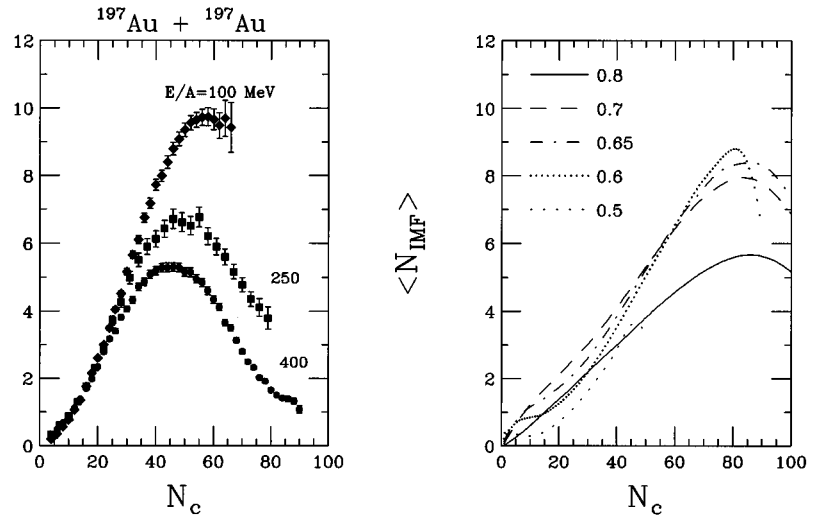

FIG. 2. Experimental data [7] and percolation results for a ^{197}Au+^{197}Au collision. The experimental data is given for $E/A=100$, 250, and 400 MeV, the theoretical predictions refer to different bond-breaking probabilities p_0.

off randomly, which lead to slightly less IMF's. Again, differences in $\langle N_{\mathrm{IMF}}\rangle(N_c)$ (left panel) could not be observed, even though there appears to be a slight improvement. However, for both isotopes, in comparison to the simulation without stability criterion, the ratio of IMF's to lighter particles decreased. In $\langle N_{\mathrm{IMF}}\rangle(N_n)$, naturally higher neutron multiplicities are observed, the ratio of the maxima positions (32/40=0.8) remains compatible with the ratio of neutrons between the isotopes, though.

The third row of Fig. 1 results from a simulation of a fission mechanism: an unstable fragment is broken into two fragments, if such a secondary fragment is unstable, it is again broken up into two fragments, and so on, until only stable fragments remain. The distribution of the secondary fragment sizes is chosen to be a parabola with maximum at 0.5. A simulation with a flat distribution yielded similar results, it had only very slightly less IMF's. Both these mechanisms fit $\langle N_{\mathrm{IMF}}\rangle(N_n)$ rather well, the ratio of the positions of the maxima, $31/41\approx 0.7$ is halfway between the expected 0.83 and the experimental value 0.6, however, the different heights of the maxima could not be reproduced. $\langle N_{\mathrm{IMF}}\rangle(N_c)$ again fails to show differences between the isotopes.

The forth row finally shows the result for a combination of the two mechanisms above, each unstable fragment undergoes evaporation or fission with equal probability. Apparently, this mechanism produces too many light fragments, both charged particles and neutrons. The ratio of the maxima in the IMF distribution versus number of neutrons is 33/44 $=0.75$.

In deviation from the established percolation models, we also worked with different breakup probabilities for bonds between protons and protons, neutrons and neutrons, and protons and neutrons, that is, a probability p_{0e} for equal pairings, and a probability p_{0d} for unequal pairings, $p_{0e}\geqslant p_{0d}$. As it turns out, in this method the outcome depends significantly on the distribution of protons and neutrons on the lattice: Amongs others, we worked with a highly ordered configuration where except for the excess neutrons both types of nucleons are distributed in an alternating way (''salt crystal''). So in this configuration, in general every proton has six neutrons as nearest neighbors and vice versa, the excess neutrons being put in randomly as ''impurities.'' As a result, we noted significant differences between both Sn isotopes in the distribution of intermediate mass fragments versus charged particles. Even though this effect leads to a closer resemblance of the experimental data, we consider it to be an artifact since it nearly completely vanishes with a purely random distribution of protons and neutrons on the grid. We attribute this effect to the fact that in a pure ''salt-crystal'' configuration every bond has the breakup probability p_{0d}; every impurity will in general lead to the introduction of six bonds with breakup probability p_{0e}, and therefore has a large impact. As a result, disregarding surface effects, in the collision between the lighter isotopes about 79% of the bonds are of type p_{0d} and 21% of type p_{0e}, while for the heavier isotopes the percentages are 61 and 39, respectively. In the random configuration, however, there is no such amplification, the percentages are 58 versus 42 for the lighter isotope, and 56 versus 44 for the heavier isotope.

Also, simulations were run with a ''neutron skin,'' which influenced the ratio of protons and neutrons in the overlap zone for different impact parameters: for small impact parameters the ratio of neutrons to protons was higher than for large impact parameters, the size of the neutrons skin were determined by a Hartree-Fock calculation [9]. However, these simulations could not improve the agreement with experimental data.

In conclusion, the experimental results could only be reproduced in part. The main discrepancies are (i) The difference between the two isotopes in $\langle N_{\mathrm{IMF}}\rangle(N_c)$ could not be reproduced. This was found to be independent of fragment-stability considerations; (ii) The difference in the maximum values of $\langle N_{\mathrm{IMF}}\rangle(N_n)$ could not be reproduced; (iii) The experimental positions of the maxima in $\langle N_{\mathrm{IMF}}\rangle(N_n)$ is incompatible with the simple shifting due to the higher neutron abundance that is found in the simulation.

The discrepancies found between the data and this basically geometrical approach indicate that effects outside of percolation theory are important. The nuclear structure of the fragments as well as sequential feeding might play a role.

Most important, however, seems the role of pre-equilibrium emission, which may not only effect the sorting axis but as well determines the N/Z composition of the fragmenting system.

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