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Mechanism for nuclear disassembly of the Ar + Th and Pb + Au systems at intermediate energies

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We show that the neutron multiplicities observed in the reaction ^{40}Ar on ^{232}Th at incident energies between 27 and 77 MeV per nucleon are consistent with the predominantly binary character of the collision process. The most violent encounters lead to excitation energies of several MeV per nucleon, sufficiently high to crack the colliding nuclei into many small fragments. We also give the neutron multiplicity and decay pattern for the reaction ^{208}Pb on ^{197}Au at 29 MeV per nucleon, for which some preliminary data is available.

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For weakly excited nuclei the dominant decay channels are light-particle evaporation and fission. On the other extreme, for excitations exceedings the total binding energy of the nucleus the decay predominantly takes place into light fragments such as nucleons, deuterons, ^{3}H, ^{3}He, and α particles. Between these two limits there is a regime where several intermediate mass fragments are produced. The observation of these multifragmentation processes provides valuable information on the behavior of nuclear matter under extreme conditions. Recent experimental results for reactions induced by ^{40}Ar on ^{232}Th at energies between 27 and 77 MeV per nucleon [1] and ^{208}Pb on ^{197}Au at 29 MeV per nucleon [2] are, in this regard, particularly interesting. Charge distribution of the fragments produced in these collisions measured as a function of the associated neutron multiplicity provide direct information on the relative violence of the processes. This makes it possible to investigate the mechanism for disassembly of hot nuclear matter in a wide interval of excitation energies.

According to our analysis, even the highest multiplicity events do not originate from the decay of a compound nuclear system, but arise from the individual decay of the colliding partners. In this picture, low multiplicities result from peripheral collisions which give rise to the moderate excitation energies that favor fission and particle evaporation. The high-multiplicity events are associated with more central collisions, leading to excitations energies exceeding 5 MeV per nucleon and thus sufficient to crack the colliding nuclei into many fragments. It is interesting to note that, for the highest excitations, the hot transient nuclear systems decay predominantly into small fragments with equal number of neutrons and protons; this mechanism releases the largest possible number of free neutrons.

To cover the dynamical aspect of the collision in the approach phase we have used the heavy-ion reaction code TORINO [3]. This treatment yields the full distribution of excitation energies for both projectile and target [4]. Provided with this information one can then proceed to calculate the subsequent decay of the reaction partners. To this end we exploit the Copenhagen multifragmentation model. Here the primordial fragment distribution after the prompt breakup is first calculated within the statistical model of Ref. [5]. As a second step, one follows the evaporation processes of the primarily formed fragments [6].

As can be seen from Fig. 1(a), the total energy loss at

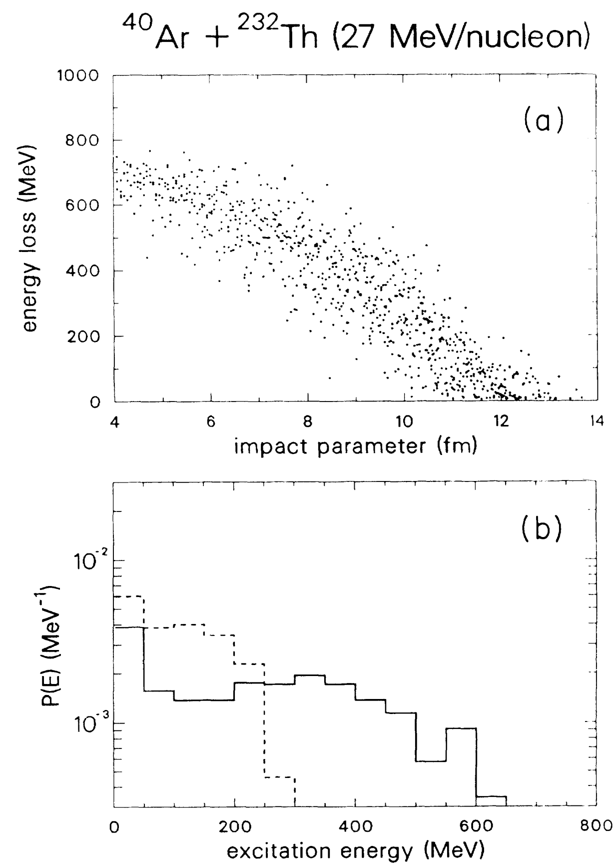

FIG. 1. (a) Distribution of transferred energy as a function of the impact parameter for the reaction ^{40}Ar on ^{232}Th at an incident energy of 27 MeV per nucleon, calculated considering an ensemble of 1000 trajectories. (b) Probability for exciting the colliding nuclei for the reaction ^{49}Ar (dashed line) on ^{232}Th (solid line) at 27 MeV per nucleon.

incident energy 27 MeV per nucleon displays large fluctuations as a function of the impact parameter. Thus the excitation energy and consequently the final neutron multiplicity cannot directly be correlated with the impact parameter, as has been speculated. In Fig. 1(b) we also give—for the same boundary energy—the reaction cross section as a function of excitation energy for both projectile-like and target-like systems.

In Fig. 2 we show the cross sections for the neutron multiplicities in the reaction ^{40}Ar on ^{232}Th together with the experimental results of Ref. [1]. While the statistical resolution of the calculations precludes a comparison at the level of details the overall agreement with the data is good. It is worth mentioning that in our model almost all of the neutrons produced in the reaction do not originate in the initial breakup of the transient binary system but are due to the decay of the hot primordial fragments. It also follows from our calculation that the local maximum at the higher multiplicities is associated with the onset of multifragmentation and contains contributions from a relatively broad energy interval. At a beam energy of 77 MeV per nucleon the decrease of the total cross section exhibited by the data is not satisfactorily reproduced.

The dynamical calculations in the entrance configuration were not deemed reliable for the most central collisions. As a consequence, the distributions reported in Fig. 2 only accumulate about 85–75 % of the reaction cross sections depending on the bombarding energy. The model in its present form does not describe the cross sections measured for very low multiplicities. This is so mainly because contributions from direct-transfer processes in peripheral reactions are not included. Furthermore, we should note that ordinary fission processes are poorly treated in the multifragmentation model. These two mechanisms are expected to contribute mostly to neutron emission at very low energies, where the multifragmentation picture does not apply. A contribution to the low neutron multiplicities from long-lived dinuclear configurations cannot, on the other hand, be excluded.

It is interesting to study the behavior of the neutron multiplicity for much heavier systems. In Fig. 3 we show the results of a calculation for the reaction induced by ^{208}Pb on ^{197}Au at an incident energy of 29 MeV per nucleon. We do not compare them to the experimental data of Ref. [2], since it is not corrected for detector efficiency. The results follow, however, a similar trend to that of the raw data; they exhibit, in particular, the bump structure at high neutron multiplicities already encountered in the previous example. We also show in Fig. 3 the charged-

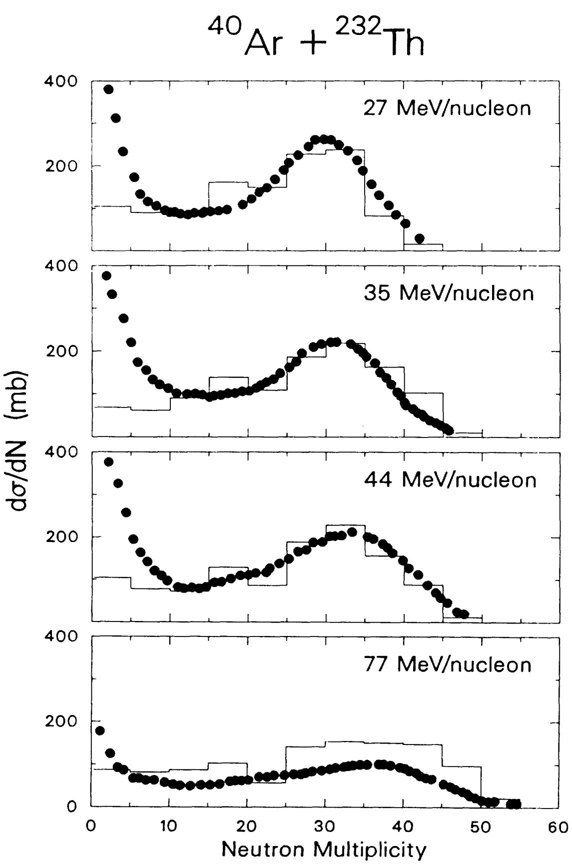

FIG. 2. Cross sections for neutron multiplicities for the reaction ^{40}Ar on ^{232}Th at incident energies between 27 and 77 MeV per nucleon [1] are compared to the prediction of the calculation described in the text (histograms), which consider a binary collision process followed by statistical multifragmentation of the excited ^{40}Ar and ^{232}Th nuclei.

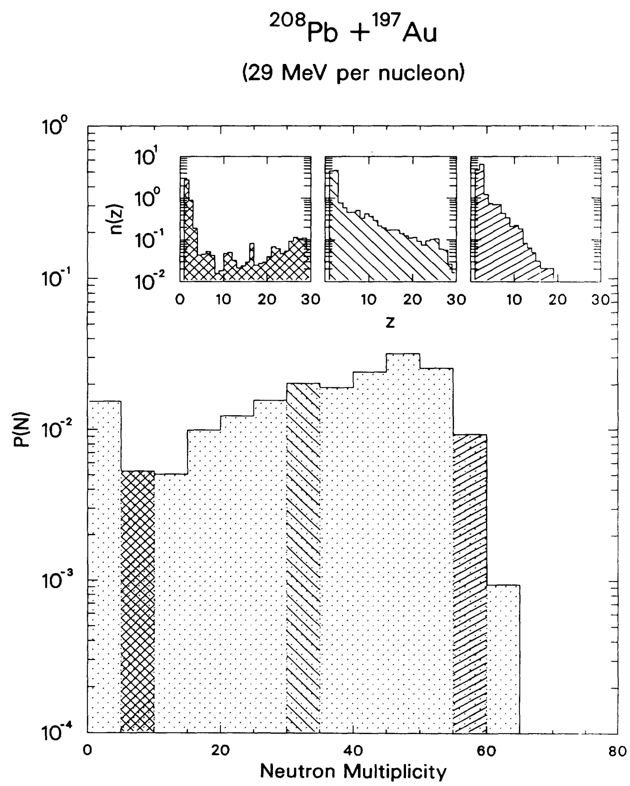

FIG. 3. Cross sections for neutron multiplicities for the reaction ^{208}Pb on ^{197}Au at an incident energy of 29 MeV per nucleon calculated by considering a binary collision process followed by statistical multifragmentation. The insets show the charged fragment distributions for the collisions having average neutron multiplicities indicated by the hatched areas.

fragment distributions for the fragmentation patterns associated to three values of the average neutron multiplicity. They show a gradual change from the characteristic U shape at relatively low excitation energies to one indicating the disintegration of the system into many small pieces. Because neutron production tends to saturate at the higher energies, the theoretical multiplicity distributions cannot be associated to a single excitation energy. The calculated trend is, nevertheless, in qualitative agreement with the experimental findings.

In summary, we have shown that the neutron multiplicities measured in the reactions ^{40}Ar on ^{232}Th at energies between 27 and 77 MeV per nucleon and ^{208}Pb on ^{197}Au at 29 MeV per nucleon can be explained by employing a two-stage scenario based on a binary description of the collision process. A semiclassical model that goes beyond the ordinary mean field approximation has been used to calculate the energy transferred from the relative motion to internal excitation of the colliding nuclei. The subsequent breakup of the highly unstable reactants has been described by means of a statistical multifragmentation model. We find that the observed neutrons are mostly produced during the decay of the primordial hot fragments. It was shown that the calculated charge distribution depends drastically on the neutron multiplicity. The calculations indicate that relatively large fluctuations in excitation energy are needed to describe the data. On the other hand, this feature makes it difficult to establish a firm correlation between impact parameter and neutron multiplicity.

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[1] U. Jahnke *et al.*, Proceedings of the XX International Summer School on Nuclear Physics, Mikolajki, 1988 (Report HM1-B 463, 1988); J. Galin, Proceedings of the XXI International Summer School of Nuclear Physics, Mikolajki, 1990 (Report GANIL P-90-17).

[2] E. Piasecki *et al.*, Phys. Rev. Lett. **66**, 1291 (1991).

[3] C. H. Dasso and G. Pollarolo, Comput. Phys. Commun. **50**, 341 (1988).

[4] R. A. Broglia, C. H. Dasso, and A. Winther, in Proceedings of the International School of Physics "Enrico Fermi" on Nuclear Strucutre and Heavy Ion Collisions, edited by R. A. Broglia, C. H. Dasso, and R. Ricci (North Holland, Amsterdam, 1981), p. 327; C. H. Dasso, in *Proceedings of the La Rabidia International Summer School on Theory of Nuclear Structure and Reactions,* edited by G. Madurga and M. Lozano (World Scientific, Singapore, 1986), p. 398.

[5] J. P. Bondorf, R. Donangelo, I. N. Mishustin, C. J. Pethick, H. Schulz, and K. Sneppen, Nucl. Phys. **A443**, 321 (1985); J. P. Bondorf, R. Donangelo, I. N. Mishustin, and H. Schulz, *ibid.* **A444**, 460 (1985).

[6] H. W. Barz, J. P. Bondorf, K. Sneppen, and H. Schulz, Phys. Lett. B **244**, 161 (1990).