Correlations between Projectilelike and Targetlike Fragments in the Reaction ^{27}Al + 44-MeV/nucleon ^{40}Ar

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Correlations between projectilelike and targetlike fragments have been measured in the reaction ^{27}Al+44-MeV/nucleon ^{40}Ar. These correlations can be consistently interpreted in the framework of an abrasion model including dissipation. However, they can also be described by a binary process in which, before decaying sequentially by particle emission, projectile and target share an approximately equal amount of excitation energy with no significant mass transfer.

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For projectiles of intermediate energies (20 to 100 MeV/nucleon), peripheral collisions between heavy ions have recently been subjected to extensive studies,[1-4] motivated by a possible rapid change[5] in the reaction mechanism as the projectile velocity becomes comparable to the velocity of the nucleons inside the nucleus. Such a transition is suggested by a rapid broadening of the projectilelike-fragment (PLF) momentum distributions[6] between 20- and 40-MeV/nucleon projectile energy. This increase in momentum width is expected in a transition from transfer to abrasion, due to the opening of the phase space made available to the nucleons removed from the projectile.[7,8] Very schematically, for projectile energies smaller than ~20 MeV/nucleon, most of these fragments are considered as the remnants of an incomplete fusion process in which only part of the projectile fuses with the target,[9] wheres for energies greater than 200 MeV/nucleon, they are thought to be produced by a fast removal (abrasion) of the nucleons in the region of overlap between projectile and target.[10] Thus, it would be interesting to determine over which energy range the transition between those two processes occurs. However, the other PLF properties (angular distributions, isotopic ratios, energy damping) evolve smoothly from the low-energy regime to relativistic energies, showing hardly any evidence of a change in the reaction process. Thus, PLF properties alone do not appear as a sensitive probe of the reaction mechanism. A better signature could be the amount of linear momentum imparted to the target since in the hypothesis of massive transfer, the nucleons removed from the projectile are captured by the target to which they communicate their linear momentum, whereas in the case of abrasion, only a small fraction of this momentum is imparted to the target through friction forces. Thus, the onset of abrasion should manifest itself by a sharp drop in the linear momentum imparted to the targetlike fragments (TLF's).

To better determine the underlying reaction mechanism in the expected transition energy region, we have measured the mass, angular, and velocity correlations between PLF's and TLF's in the reactions induced by 1760-MeV ^{40}Ar on ^{27}Al, for which there already exist extensive inclusive data on PLF's.[11]

The experiment was performed using a 44-MeV/nucleon ^{40}Ar beam at the Grand Accélérateur National d'Ions Lourds facility. In order to reduce energy and angular straggling of the TLF's the self-supported ^{27}Al target was only 100 μg/cm^2 thick. The PLF's were identified by their charge and mass using a time-of-flight spectrometer[11] subtending a solid angle of 2.5×10^{-5} sr, and positioned at 3.1° relative to the beam direction.

The targetlike fragments were detected in a battery of eight 300-mm^2-area silicon detectors, the thickness of which (300 and 500 μm) was sufficient to stop all target fragments. These detectors, each subtending a solid angle of 0.71 msr, were positioned 10° apart at 60 cm from the target. They were located in the same plane as the time-of-flight spectrometer on the other side of the beam and covered the angular range from 15° to 85°.

The low kinetic energy (5 to 20 MeV) of the TLF's did not allow charge identification. However, from the energy of these fragments and from their time of flight, it was possible to determine their mass. After corrections for plasma delay, using the velocity of elastically scattered ^{27}Al nuclei, and for pulse-height defects[12] in the detectors, a complete mass identification of the TLF's was achieved down to the detection threshold energy of ~3 MeV for all masses. Mass, charge, velocity, kinetic energy, and emission angle of PLF's and the corresponding quantities (except the charge) of the TLF's were determined for each coincidence event.

Figure 1 shows the PLF-TLF mass correlation which was obtained by considering the full angular range of the TLF's between 15° and 85°. The data points represent the ridge of the correlation, whereas the horizontal (vertical) bars indicate the full width at half maximum (FWHM) of the PLF's and (TLF's) mass distributions for a given mass of the TLF's (PLF's). On average, the mass lost by the target is equal to the mass lost by the projectile.

The angular distribution of the TLF's were fitted by Gaussians in order to determine the average TLF recoil angle as a function of the mass of the associated PLF's [Fig. 2(a)]. As the mass of the detected PLF's increases, the recoil angle of the associated TLF's gets larger, reaching a value close to the elastic recoil angle for PLF's approaching the projectile [Fig. 2(a)]. At the same time, the velocity of the TLF's increases rapidly as their mass decreases [Fig. 2(b)].

The observed mass-mass correlation (Fig. 1) suggests at first an abrasion process in which an approximately equal number of nucleons is removed from projectile and target. Recently, an extended version[11] of the simple geometrical abrasion model[13] was, in fact, successful in reproducing the mass distribution and the average kinetic energy of the PLF's in the same reaction.[11] In this model, it is assumed that the energy damping of the fragments results essentially from the energy dissipated in order to split the projectile or (and) target into a spectator and a participant, whereas only a small amount of excitation energy (less than 50 MeV) is imparted to the primary fragments.[11]

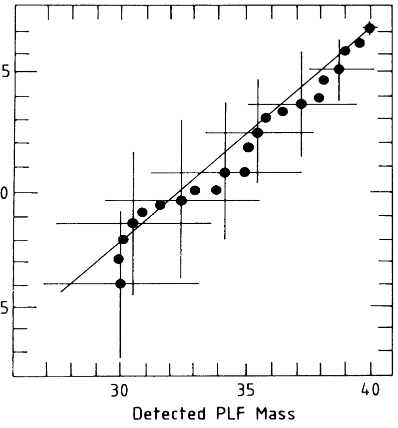

FIG. 1. Detected mass of the TLF's vs the detected mass of the PLF's. The full drawn curve is the result of a calculation in the framework of an abrasion-ablation model.

The masses of the secondary fragments were obtained using the code LILITA[14] to estimate the number of evaporated particles from the excited fragments. The predicted mass-mass correlation and the recoil velocity of the TLF's are shown by the full lines in Figs. 1 and 2(b), respectively. The TLF recoil angle [full line in Fig. 2(a)] as a function of the PLF mass was obtained through momentum conservation and by assuming that the average momentum of the unobserved participants is in the beam direction. All the main features of the data are very well reproduced, which seems to support the presence of such a process.

The above mechanism is basically a multiparticle process in which the observed PLF's and TLF's are the remnants of primary fragments left over after a first ejection of a large number of fast nucleons. The dependence of the TLF recoil angle upon the PLF mass is, however, reminiscent of a more simple two-body mechanism where only two excited primary fragments emerge from

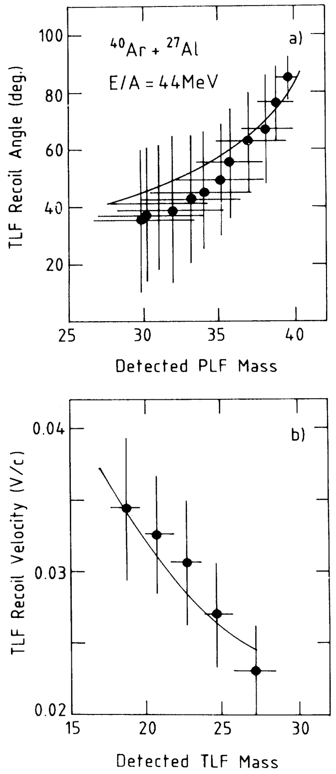

FIG. 2. (a) Average recoil angle of the TLF's as a function of the mass of the associated PLF's. The vertical and horizontal bars represent the FWHM of TLF angular correlation and of the PLF mass distribution, respectively. The full drawn curve is the result of an abrasion-ablation calculation. (b) Average recoil velocity (in units of c) of the TLF's as a function of their mass in bins of two mass units as indicated by the horizontal bars. The vertical bars are the FWHM of the velocity distributions. The full drawn curve is the result of an abrasion-ablation calculation (see text).

the collision, which then decay by particle emission.[15] In order to test this possibility, we have performed an event by event analysis of the data using the following hypotheses: (i) The primary reaction is a two-body reaction, (ii) the excited primary fragments are individually in thermal equilibrium and decay by light-particle emission, and (iii) the average velocity and direction of the fragments are not modified by the evaporation process. Then momentum conservation can be used for a full kinematic reconstruction of the binary events,[15] which yields primary quantities like fragment masses, excitation, and kinetic energies. The average primary masses of the PLF's and of the TLF's have been *independently* reconstructed and are shown as functions of the detected PLF mass in Figs. 3(a) and 3(b). We note that, within one mass unit, the PLF and TLF primary masses add up to the sum of the projectile and target masses as they should in a two-body process, and that they remain very close to those of the projectile and of the target with a net average mass transfer from projectile to target not exceeding two mass units. Furthermore, the widths (FWHM) of the primary mass distributions [vertical bars in Figs. 3(a) and 3(b)], although increasing when the detected PLF mass decreases, remain relatively small ($\leqq 7$ mass units). The evaporation process as well as the angular and energy straggling in the target of the detected TLF's contribute significantly to those widths which should be considered as upper limits. Thus these results invalidate massive transfer either from the projectile to the target or from the target to the projectile as a main reaction mechanism.

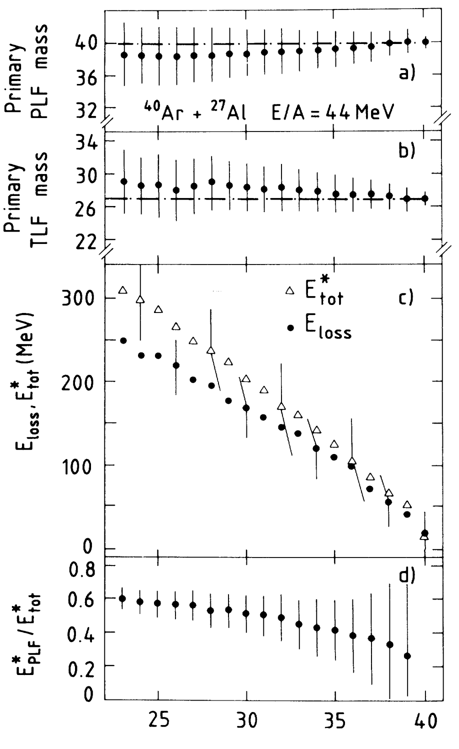

FIG. 3. Masses of the (a) primary PLF's and (b) primary TLF's as functions of the mass of the detected PLF's. The masses of the projectile and of the target are indicated by the horizontal dotted-dashed lines. (c) Total kinetic-energy loss (●) and total excitation energy (△) of the primary fragments of functions of the measurement PLF mass. (d) Fraction of the excitation energy imparted to the primary PLF's as a function of the measured PLF mass. The vertical bars are the FWHM's of the reconstructed distributions.

The total kinetic energy loss to the primary fragments, derived from the kinematics, is compared in Fig. 3(c) to their total excitation energy as a function of PLF detected mass. The excitation energies E^*_{PLF} and E^*_{TLF} of the primary PLF's and TLF's were obtained using the code LILITA[14] in which the primary mass distributions were given as input and the excitation energies were adjusted until the mass distributions of the final products agreed with the experimental ones. For a true two-body reaction and in the absence of nonequilibrium emission of particles, the total excitation energy E^*_{tot} imparted to the fragment, except for a small contribution from the ground-state Q values which has been neglected, should be equal to the kinematically determined total kinetic-energy loss E_{loss}. It is found [Fig. 3(c)] that for the lightest detected PLF's, the total excitation energy, although consistent with the total kinetic-energy loss, is somewhat larger. This slight discrepancy may in part originate from uncertainties in the evaporation calculations. Alternatively, this difference between E^*_{tot} and E_{loss} could be imputed to an emission of fast nucleons or an evaporation of light particles prior to the separation of the fragments. Emission of less than five nucleons with about half the beam velocity (in the laboratory frame) would be sufficient to explain the observed difference between E^*_{tot} and E_{loss}. In contrast, for the same reaction, recent calculations[16] performed in the framework of Landau-Vlasov dynamics, for an impact parameter of 7 fm, predict an emission of ~ 15 fast nucleons for a 45-MeV/nucleon projectile.

The ratio $E^*_{\mathrm{PLF}}/E^*_{\mathrm{tot}}$ of the excitation energy in the primary PLF's to the total excitation energy of the system is reported in Fig. 3(d) as a function of the mass of the detected PLF's. Although this ratio may be consistent with an almost equal sharing of the excitation energy between projectile and target, it tends to decrease as the mass of the detected PLF's increases (or the energy loss decreases). The primary mass distributions indicate no net mass transfer between projectile and target, suggesting that an about equal number of nucleons has been exchanged between projectile and target. This exchange process should be at the origin of the excitation energy in the primary fragments and could explain the slight target dependence[17] of the PLF average neutron-to-proton ratio. The same process has been invoked[18,19] to explain why in deeply inelastic collisions, for small energy loss (or short interaction times), the excitation energy divides almost equally between projectile and target, whereas for large energy losses (or long interaction times), it approaches the ratio of the primary fragment masses.[20,21] At the present energy the interaction time could always be too short to allow thermal equilibrium between projectile and target.

In contrast with the prediction of the abrasion model, in the present two-body description, the primary fragments carry a much larger amount of excitation energy which increases almost linearly as the mass of the observed fragment decreases. This behavior is consistent with the recently observed increase of the charged-particle multiplicity as the Z of the PLF's decreases.[22]

In conclusion, we have observed strong correlations between the properties of the projectilelike and targetlike fragments in the intermediate-energy regime. A coherent description of the data can be obtained in the framework of the abrasion model commonly used to describe projectile fragmentation. However, our analysis has shown that the observed correlations are also consistent with a primary two-body process, reminiscent of the early stage of deeply inelastic collisions, in which projectile and target share an approximately equal amount of excitation energy. Recent measurements of the charged-particle multiplicities associated with the projectilelike fragments seems to favor this second hypothesis. Fragment-correlation measurements in more asymmetric systems or measurements of the excitation energy imparted to primary fragments should help to solve the above ambiguities.

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[1] R. G. Stokstad, Comments Nucl. Part. Phys. **13**, 231 (1984).

[2] D. Guerreau, Nucl. Phys. **A447**, 37c (1986).

[3] R. Dayras, J. Phys. (Paris), Colloq. **47**, C4-13 (1986).

[4] G. Bizard, J. Phys. (Paris), Colloq. **47**, C4-35 (1986).

[5] M. Buenerd *et al.*, Phys. Rev. Lett. **37**, 1191 (1976).

[6] C. K. Gelbke *et al.*, Phys. Lett. **70B**, 415 (1977).

[7] W. A. Friedman, Phys. Rev. C **27**, 569 (1983).

[8] H. Utsunomiya, Phys. Rev. C **32**, 849 (1985).

[9] J. Wilczynski *et al.*, Phys. Rev. Lett. **45**, 606 (1980); B. G. Harvey and M. J. Murphy, Phys. Lett. **130B**, 373 (1983).

[10] A. S. Goldhaber and H. H. Heckman, Annu. Rev. Nucl. Part. Sci. **28**, 161 (1978).

[11] R. Dayras *et al.*, Nucl. Phys. **A460**, 299 (1986).

[12] S. B. Kaufman *et al.*, Nucl. Instrum. Methods **115**, 47 (1974).

[13] J. D. Bowman, W. J. Swiatecki, and C. F. Tsang, Lawrence Berkeley Laboratory Report No. LBL-2908, 1973 (unpublished).

[14] J. Gomez del Campo and R. G. Stokstad, Monte Carlo Statistical-model code LILITA, in Oak Ridge National Laboratory Technical Memo No. ORNL-TM-7295, 1981 (unpublished).

[15] R. Babinet *et al.*, Nucl. Phys. **A296**, 160 (1978).

[16] C. Grégoire, B. Rémaud, F. Sébille, and L. Vinet, Phys. Lett B **186**, 14 (1987).

[17] D. Guerreau *et al.*, Phys. Lett. **131B**, 293 (1983).

[18] J. Randrup, Nucl. Phys. **A383**, 468 (1982).

[19] L. G. Moretto, Z. Phys. A **310**, 61 (1983).

[20] T. C. Awes *et al.*, Phys. Rev. Lett. **52**, 251 (1984).

[21] D. R. Benton *et al.*, Phys. Lett. B **185**, 326 (1987).

[22] G. Bizard *et al.*, Phys. Lett. **172B**, 301 (1986).