Probing time scales in projectile fragmentation processes at intermediate energies

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Distorting effects of the target Coulomb field are exploited to learn about the time scales for projectile disintegration in heavy-ion grazing collisions at intermediate energies. A global variable that can be used for this purpose is suggested.

The complete breakup of light projectiles in peripheral collisions with heavy nuclei has been recently observed [1]. Attempts have been made to determine whether the splitting of the highly excited projectile takes place instantaneously or following a sequence of binary, fission-like steps. To this end one exploits the effects of the Coulomb interaction on the asymptotic motion of the reaction products. If the fragments are generated simultaneously—and thus in close proximity—they strongly affect each others' trajectories of relative motion. If, instead, each new pair is created far apart from the preceding fragments, correlations between the final momenta of the outgoing reaction products are minimal.

To learn about the shape of the emitting source, individual events are represented in the sphericity-coplanarity (*S-C*) plane defined from the eigenvalues of the momentum tensor [2–4]. Since this quantity is constructed in the reference frame of the disintegrating projectile, all distributions in the sphericity-coplanarity plane become practically independent of the presence of the target.

In this contribution we set out to investigate distortions in the distributions of the breakup products that can be attributed to the target Coulomb field (cf., e.g., Ref. [5]). For this purpose we discard the aforementioned prescription and work in what follows with velocities (rather than momenta) defined in the center of mass of the reaction. Within this context it is rather natural to consider the possibility of using the slow radial dependence of the electrical forces to probe the characteristic distances at which the decay actually occurs.

Our objective is to identify, via event simulation, appropriate variables that can be used to reveal the nearby presence of the target. The magnitude of these effects should, in turn, yield quantitative information on the time delay involved in the projectile breakup. We shall illustrate these points using as an example the same reaction as in Ref. [1], namely, $^{16}O+^{197}Au$ at 32.5 MeV/nucleon. The fact that the experimental setup identifies quite reliably the fragments of the projectilelike system underscores the peripheral character of the collision. This, and the relatively low incident energy,

places our study in a regime where a point of contact with heavy-ion grazing processes at lower bombarding energies can be established. According to these considerations we have used a heavy-ion reaction code [6] to generate the initial conditions of a highly excited projectile whose sequential disintegration follows. This picture of the evolution of a heavy-ion collision has been advocated specially by Moretto [7]. This procedure yields both the relative position and momentum of the ions at the instant in which the first splitting is set to occur. We set the origin to measure times, $t=0$, at the distance of closest approach and trigger the subsequent analysis by generating a sequence of binary decay steps with lifetimes τ_i. Several decay chains can be contemplated, for instance, $O \rightarrow C+\alpha \rightarrow Be+\alpha+\alpha \rightarrow 4\alpha$ or $O \rightarrow Be+Be \rightarrow Be+\alpha+\alpha \rightarrow 4\alpha$. Here we consider only the former, with expected lifetime ratios $\tau_1:\tau_2:\tau_3$ as 55:40:5; from simple Q-value considerations this is in fact the most likely to occur. For such a sequence the total lifetime is $\tau=\sum_i \tau_i$, and we study the characteristics of the process as a function of τ. At all stages the time intervals between the decay steps are generated according to the statistical law for the corresponding lifetimes. Therefore, our simulation of a large number of events (typically in the order of 10^4–10^5) actually samples the full distribution of decay times that yield the average value τ.

At each step of the decay chain the two fragments are released with random orientations, assuming a saddle configuration corresponding to that of two touching spheres. If the excitation energy of the decaying system in the step i is called $E^*(i)$, the excitation energy available for the next decay in the chain is constructed with

$$E^*(i+1)=E^*(i)+Q-V_C-K(i) , \qquad (1)$$

where Q is the Q value for the specified mass partition, V_C is the Coulomb interaction energy, and $K(i)$ is the released kinetic energy. The quantity K is assigned values according to the exponential distribution law $P(K)=\lambda \exp(-\lambda K)$, where $\lambda=\sqrt{a/E^*}$ and a is the density parameter for the decaying fragment.

The position and velocity of all particles along the de-

cay chain are generated in such a way as to conserve linear momentum and to preserve the position of the total center of mass. Eventual effects associated with the intrinsic angular momentum of the source have been ignored. The Coulomb expansion of the reaction products is followed up to a point in which asymptotic, i.e., noninteracting, motion of all the fragments is reached. In solving the corresponding system of coupled classical equations the presence of the target—and its motion—is taken into account.

To illustrate the procedure we are going to follow we show in Fig. 1 the contours of the velocity distributions for the projectile fragments and target. Results for two lifetimes are shown. On the left-hand side we illustrate a situation where the entire decay takes place in close proximity to the target (τ=40 fm/c). The right-hand side of the figure displays, instead, the velocity distribution for all particles assuming that the disintegration of the projectile is completed far away from the target (τ=800 fm/c). In these calculations the orientation of the beam was set along the x axis, and all azimuthal angles around this direction have been included. Density contours are given in the v_x-v_y plane (identical to those in the v_x-v_z plane) and also in a radial representation specified by $v_p = \sqrt{v_y^2 + v_z^2}$ and v_x. We note that for these peripheral conditions the scattering angle is very small and does not cause a significant spread of the velocities off the x direction (as can be inferred from the frame for $t = 800$ fm/c).

The two situations depicted in Fig. 1 indicate that the effects of the electric field of the target are potentially capable of discriminating between different time scales in the projectile disintegration. The suppression of events with very small relative velocity due to the mutual Coulomb repulsion has also been advocated as a means to discriminate between the sequential and multifragmentation mechanisms in the formation of intermediate mass

fragments (IMF) [8,9]. Here we use the field of the target to infer the lifetime of the excited projectile assuming a sequential decay mechanism.[1]

In order to characterize quantitatively the distortions in the velocity distributions depicted in Fig. 1, we propose the application of a quadratic-form analysis to the velocity distributions themselves and the exploitation of the already familiar concepts of sphericity, coplanarity, and eccentricity (ϵ) to describe their shape. To this end we use the final velocities of all projectile fragments for N generated events to construct a normalized velocity tensor

$$\mathbf{V}_{ij} = \frac{1}{4N} \sum_{v=1}^{4N} (v_i^{(v)} - \bar{v}_i)(v_j^{(v)} - \bar{v}_j) , \qquad (2)$$

where

$$\bar{v}_i = \frac{1}{4N} \sum_{v=1}^{4N} v_i^{(v)} . \qquad (3)$$

A diagonalization of this matrix yields the eigenvalues that are necessary to define the global variables [3].

The results of a series of calculations where τ has been varied are shown in Fig. 2. The coplanarity C displays a smooth, monotonic behavior which lends itself to a calibration of the time scale. The sphericity and eccentricity variables are not shown since in this case they are simple functions of the coplanarity. The range of variation of C in Fig. 2 may appear rather narrow. We note, however, that in this case the definition of the velocity distributions can be made with arbitrary precision by increasing the number N of events included in Eq. (2). Thus, the proposed analysis is not subject to the statistical limitations associated with the small multiplicity of the event [11].
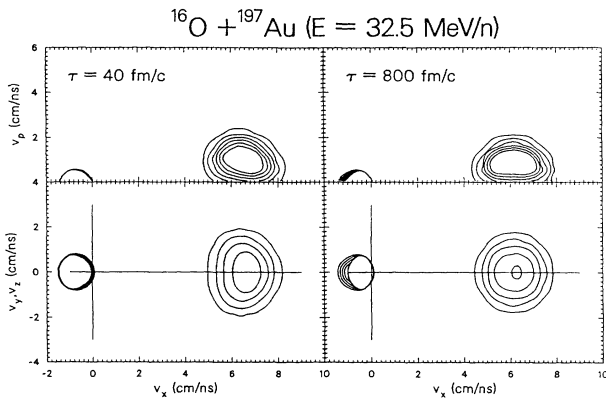

FIG. 1. Contours of the velocity distributions for the outgoing particles in the center-of-mass system of the reactions $^{16}O + ^{197}Au$ at $E = 32.5$ MeV/nucleon. The calculations are for the sequential breakup chain $^{16}O \rightarrow ^{12}C + \alpha \rightarrow ^8Be + 2\alpha \rightarrow 4\alpha$. The distributions are shown for two values of the total lifetime of the indicated decay process. Note that the cloud at the right-hand side of each frame represents the velocity of the particles coming from the projectile breakup.
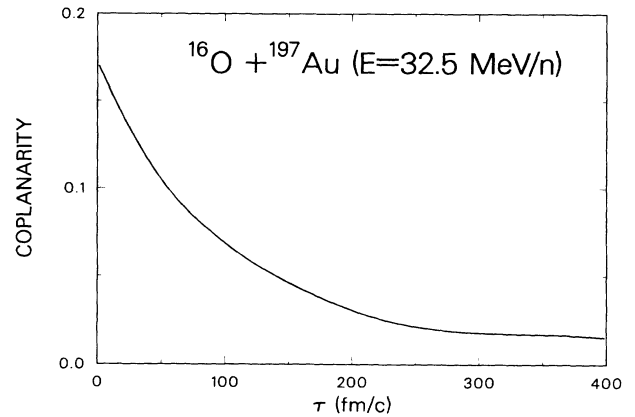

FIG. 2. Coplanarity as a function of the lifetime τ of the process, constructed from the velocity distributions of the projectile fragments.

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[1]We note that in the low-energy limit we consider here, a simultaneous creation of all final projectile fragments is not likely to be the favored decay mechanism. These multifragmentaion processes were the object of an earlier report [10].

Given the particular symmetries of the present configuration, one could have also characterized the shape of the v distributions in terms of the ratio between the variances of longitudinal and transverse components of the velocity of the final fragments; we have here chosen to exploit the eigenvalues of the velocity tensor because the prescription is readily adapted to more general circumstances. Simulations under the assumption that the reaction plane is identified do not increase the time resolution significantly. We have also checked that the admixture of other decay chains does not affect the correlation $C(\tau)$ displayed in Fig. 2.

The delays that can be probed according to the results obtained for this reaction are of the order of $\Delta t \sim 300$ fm/c (lifetimes of this order of magnitude have been recently extracted from a two-fragment correlation function in the reaction ^{36}Ar+^{197}Au at $E/A = 35$ MeV [12,13]). This value can be understood in terms of the time involved in moving away from the target to distances in which the forces between projectile fragments become comparable to the one exerted by the target, i.e.,

$$\Delta t \sim \left[\frac{Z_T}{Z_F} \right]^{1/2} \frac{2R_P}{v_{PT}} \ . \tag{4}$$

Here P and T stand for projectile and target, v_{PT} is their relative velocity, and Z_F is a characteristic value for the charge of the fragments. Since the values of the parameters entering in this formula cannot be varied widely, one should not expect the sensitivity of this prescription to extend to a much larger range than the one exhibited by the present example. The obtained scale is, however, adequate to cover any processes occurring within distances comparable to the nuclear dimensions.

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