Binary Character of Highly Dissipative ${}^{209}\text{Bi} + {}^{136}\text{Xe}$ Collisions at $E_{\text{lab}}/A = 28.2$ MeV

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Exclusive measurements of neutrons and charged products have been performed using a combination of 4π neutron and 4π charged-particle detectors. The maximum observed energy dissipation corresponds to only approximately one-half of the available kinetic energy. For any degree of dissipation, the velocity distributions of charged particles are characteristic of sequential emission following binary collisions. The data imply that central collisions also lead to bimodal emission patterns or that they are not sufficiently well isolated by the requirement of high particle multiplicities.

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During the last few years, considerable effort [1] has been devoted to the search for novel reaction mechanisms and nuclear decay modes that have been postulated for the Fermi energy domain [2-5]. Such novel reaction scenarios include the formation of inherently unstable, hot, and possibly compressed mononuclei that are predicted either to expand and eventually disintegrate into multiple fragments of intermediate mass (IMFs) or to vaporize into a multitude of light particles. Features similar to those expected for such processes have been observed in heavy-ion reactions at intermediate bombarding energies [6-11], but their interpretation is subject to considerable ambiguities. In order to resolve some of these ambiguities, the strategy adopted in the present work was to explore how the binary reaction dynamics characteristic of weakly dissipative, peripheral heavy-ion collisions evolves with increasing energy dissipation for the very heavy system $^{209}Bi + ^{136}Xe$ at 28.2 MeV per nucleon, i.e., at the lower boundary of the Fermi energy domain. As suggested by systematics established at lower bombarding energies [12], such a heavy system is likely to exhibit a gradual evolution of a rather uniform dissipative reaction mechanism over a significant range of impact parameters, which would simplify the detection of the onset of a new, competing process.

The present paper reports on the first experiment of its kind in which almost full solid-angle coverage for both neutrons and charged particles was achieved. The experiment was performed at the National Superconducting Cyclotron Laboratory of the Michigan State University. A beam of 28.2 MeV per nucleon ¹³⁶Xe ions from the K1200 cyclotron was focused on a self-supporting ²⁰⁹Bi target (1.5 mg/cm²) placed in the center of the internal scattering chamber of the Rochester neutron multiplicity meter (NMM). The NMM, providing information on multiplicity and summed neutron energy, has an outer

geometry close to that of a sphere of radius of 62 cm. Its active volume (900 1) is filled with Gd-loaded liquid scintillator (Bicron BC521), viewed by 12 Amperex XP2041 photomultipliers. The principle of operation of this type of detector is described in more detail in Ref. [13]. Charged reaction products were detected using the compact plastic/CsI(Tl) Dwarf Ball/Wall [14] scintillationdetector array of Washington University, installed in the NMM scattering chamber. The 63 Dwarf Ball phoswich detectors covered an angular range from 32° to 168° , while the forward region (4.6° to 32°) was covered by 32 Dwarf Wall detectors. The phoswich detectors were calibrated in energy using elastic scattering and experimental



FIG. 1. Linear contour plot of the Galilei-invariant velocity distribution for protons coincident with projectilelike fragments measured at angles between 4° and 8°. Continuity of this distribution was achieved by randomizing the detection coordinates over the faces of the corresponding Dwarf Ball/Wall detectors. The solid and dashed arcs illustrate the Coulomb velocities expected for protons emitted from Bi and Xe, respectively, with emitter velocities corresponding to an energy loss of $E_{\rm loss}$ = 500 MeV. The dotted curve indicates the threshold energies.

maximum possible energy deposits ("punchthrough energies"). Additionally, heavier reaction products, such as projectilelike fragments (PLFs) and their sequential fission products, were detected using three silicondetector telescopes viewing the target through an opening created by the removal of one of the five sectors of the (forward) Dwarf Wall.

In Figs. 1 and 2, experimental emission patterns of charged particles from the reaction $^{209}\text{Bi}+^{136}\text{Xe}$ are displayed in the form of two-dimensional maps of Galilei-invariant cross section $d^2\sigma/v_{\perp}dv_{\perp}dv_{\parallel}$, plotted versus the particle velocity components parallel (v_{\parallel}) and

perpendicular (v_{\perp}) to the beam direction. Figure 1 shows such a map for protons measured out of plane $(72^{\circ} \le \phi \le 108^{\circ})$ in coincidence with PLFs with atomic numbers of Z > 30, detected in the range $4^{\circ} \le \theta \le 8^{\circ}$ $(\phi = 0^{\circ})$ including the grazing angle of $\theta_g \simeq 6^{\circ}$. Since the coincidence requirement of a massive surviving PLF selects a range of intermediate and large impact parameters, one expects predominantly sequential particle emission from PLFs and their reaction partners [targetlike fragments (TLFs)], or their fission products. This expectation is confirmed by the data of Fig. 1, where two distinct semicircular ridges of proton yield consistent with



 $^{209}Bi+^{136}Xe$ E_{lob}/A=28.2 MeV

FIG. 2. Linear contour plots of Galilei-invariant velocity distributions (a)-(d) for protons for different multiplicities of coincident neutrons and (e)-(h) for deuterons for different multiplicities of the coincident charged particles. The multiplicity bins are defined in Fig. 3. The dip in the ridge around v_{\parallel} =4.0 cm/ns observed in the distributions (d) and (h) is due to pileup effects. Maximum energy deposits ("punchthrough energies") in the forward-angle Wall detectors are represented by dotted lines in (e)-(h).

emission from these sources are observed. The two theoretical curves in Fig. 1 represent Coulomb velocities of protons calculated for Bi (solid curve) and Xe (dashed curve) fragments from a collision corresponding to a kinetic-energy loss of $E_{\rm loss}$ =500 MeV, which is the most probable energy loss associated with these events.

Surprisingly, the experimental velocity distributions of all light charged particles from the $^{209}Bi + ^{136}Xe$ reaction exhibit a common pattern for all degrees of energy dissipation. The dissipated kinetic energy can be inferred from the multiplicities of either neutrons or various charged particles emitted in the collision, all available from the present experiment. Neutron (m_n) and charged-particle multiplicities (m_{CP}) are correlated with each other, for a wide range of dissipated energies, such that on average $m_n = 6$ and 12 correspond to $m_{CP} = 12$ and 23.5, respectively. As illustrative examples, in Figs. 2(a)-2(d) and 2(e)-2(h) the velocity distributions of protons and deuterons are shown, gated with the multiplicity of the associated neutrons and charged particles, respectively. The corresponding multiplicity bins are defined in Fig. 3, displaying the multiplicity distributions for neutrons (top) and charged particles (bottom). Each set of multiplicity bins covers essentially the total reaction cross section. The finite multiplicity resolutions of the detectors, induced by their nonunit detection probability for neutrons ($\epsilon \simeq 60\%$) and charged particles ($\epsilon \simeq 70\%$), are always smaller than the widths of the multiplicity bins chosen.

As seen in Fig. 2, proton and deuteron emission patterns evolve in a smooth systematic fashion with increasing degree of dissipation, while preserving their general bimodal character, with most of the yield concentrated in



FIG. 3. Multiplicity distributions of neutrons (top) and charged particles (bottom) as measured, requiring the detection of at least one charged particle by the Dwarf array.

two semicircular ridges. The ridge of approximately constant cross section observed at forward angles, centered around $v_{\parallel} \simeq 6.5 - 7.5$ cm/ns, corresponds to particle emission by PLFs scattered primarily at small angles. Such a distribution is incompatible with nonequilibrium emission mechanisms, like Fermi-jet or preequilibrium processes. The bimodal character of the velocity distribution, well expected for low-multiplicity bins associated with peripheral collisions, persists up to the highest particle multiplicities measured in this experiment. Similarly, as shown in Fig. 4, the velocity distribution of protons measured in coincidence with at least six IMFs ($Z_{IMF} \ge 4$) suggests the presence of the bimodal structure discussed above. This latter type of event also corresponds to highly dissipative collisions, since IMFs are associated with the highest neutron and charged-particle multiplicities and, presumably, with the most central collisions. A bimodal character is observed even for the velocity distributions of IMFs themselves.

Simplified simulation calculations were performed for the particle velocity distributions, based on isotropic emission from representative moving PLF and TLF sources. These calculations give an excellent reproduction of the data, except for a weak additional yield at $(v_{\parallel}, v_{\perp}) \approx (3.5, 5.0)$ cm/ns, most clearly seen in Figs. 2(a) and 2(e). This latter component, which is probably due to nonequilibrium processes, is compatible with the definition of a binary process adopted in this work. The feature at $v_{\parallel} \approx 5.0$ cm/ns in the velocity spectra is understood to be largely caused by the overlap of the two circular ridges, with a slight excess intensity in the most forward detectors remaining to be explained.

The velocities of the particle emitters indicated by arrows in Fig. 2 have been estimated from the integrated multiplicities, assuming a damped binary reaction scenario [15]. These velocities agree very well with the centers of the observed circular ridges in the velocity distributions for deuterons, tritons, and alpha particles. The



FIG. 4. Same as Fig. 1, expect for protons in coincidence with at least six IMFs.

agreement between these two velocities is less obvious from inspection of the proton velocity distributions, because of the significant portions of the PLF component that are below the detection threshold or masked by the corresponding component from the TLF. Consistently, these data suggest that the maximum dissipated energy does not exceed (50-60)% of the initial total kinetic energy.

Together, the above results clearly demonstrate the persistence of dissipative binary collision dynamics in the reaction ²⁰⁹Bi+¹³⁶Xe at 28.2 MeV per nucleon. Similar conclusions have been drawn in studies [16] of peripheral collisions of lighter systems. In contrast, in the present work, binary dynamics is found to dominate for all degrees of dissipation, as defined by the multiplicities of neutrons and charged particles. Even the requirement of multiple IMFs does not predominantly select a different reaction mode. From these results, one concludes either that central collisions lead also to bimodal emission patterns or that they are not sufficiently well isolated by the requirement of high particle multiplicities. The striking observation of a predominance of dinuclear dynamics in the Fermi energy regime made in this work emphasizes the need to establish experimentally the boundaries of the domain of this binary reaction mode. It also calls for consideration of this mechanism in other studies of intermediate-energy heavy-ion reactions.

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