Correlations with projectile-like fragments and emission order of light charged particles

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The 35 MeV/u $^{70}Zn+^{70}Zn$, $^{64}Zn+^{64}Zn$, and $^{64}Ni+^{64}Ni$ systems have been used to examine correlations of light charged particles (LCPs) and intermediate mass fragments (IMFs) with projectile-like fragments (PLFs). A new method was developed to examine the "flow" of the particles with respect to the PLF (PLF-flow). The PLF-flow was examined by plotting the average scaled PLF-plane momentum, $<\tilde{p}_x>$, of the fragments as a function of the scaled rapidity, $\tilde{Y}$, defined as

$$\tilde{p}_x = p_{x,frag} / p_{t,PLF} \qquad (1)$$

$$\tilde{Y} = Y_{cm,frag} / Y_{cm,PLF} \qquad (2)$$

with $p_{x,frag}$ representing the PLF-plane momentum of the fragment, $p_{t,PLF}$ representing the transverse momentum of the PLF, and $Y_{cm,frag}$ ($Y_{cm,PLF}$) equaling the center-of-mass rapidity of the fragment (PLF). This presents a method to examine the fragments in a PLF-invariant frame. The invariant PLF-scaled flow was used to examine the dynamics of the mid-rapidity proton, deuteron, triton, ^{3}He, alpha, ^{6}He, ^{8}He, Z=3, and Z=4 particles.

The slope of the $<\tilde{p}_x>$ over the mid-rapidity region can provide information about the movement of the fragments with respect to the PLF. For example, a positive slope would imply that on average the fragments are moving towards, or following, the PLF. In order to investigate the movement of the mid-rapidity fragments a linear fit was applied to the $<\tilde{p}_x>$ vs. $\tilde{Y}$ plot from $-0.1 \leq \tilde{Y} \leq 0.45$. The fit range focuses on the forward rapidity fragments since we are examining correlations with the PLF and also excludes any backward angle detector threshold effects. Fig. 1 presents $<\tilde{p}_x>$ plotted against $\tilde{Y}$ for protons, deuterons, and tritons in correlations with a Z=24 PLF. The linear fit is shown as the solid colored line for each isotope. The slope of the linear fit is then used to quantify the PLF-flow for the different particle types.

The slopes observed in Fig. 1 suggest that the mid-rapidity protons, deuterons, and tritons are moving in different directions with respect to the PLF. The positive slope exhibited by the protons would imply that they are, on average, moving toward or are more aligned with the PLF. In contrast, the tritons appear to move in the opposite directions, away from the PLF, implied by the negative slope or PLF-flow.

We propose that the different trajectories of the mid-rapidity fragments, shown in Fig. 1, are connected to their proximity to the PLF and TLF at their time of formation. Fig. 2 presents a simplified illustration of the possible effect of the PLF-TLF proximity to the mid-rapidity fragments. If the mid-rapidity fragment is emitted while in a close proximity to the PLF and TLF (left side of Fig. 2) then the Coulomb potential would likely force the fragment trajectory to be anti-aligned, or perpendicular, with

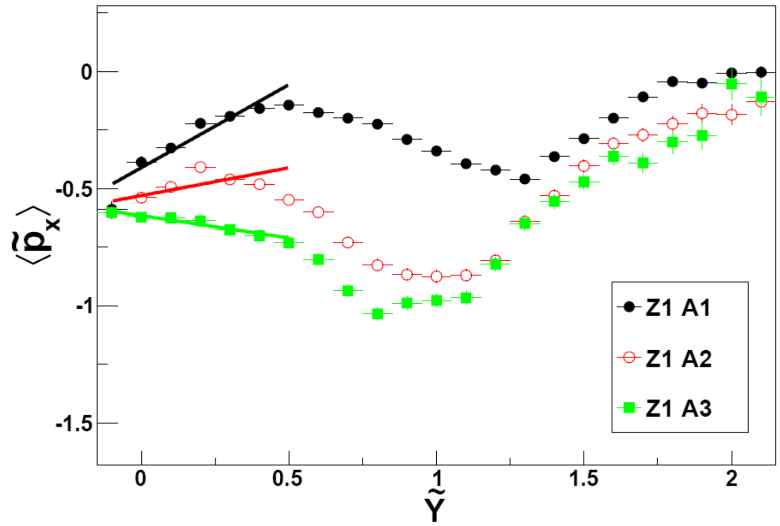

FIG. 1. The average scaled PLF-plane momentum, $<\tilde{p}_x>$, of protons, deuterons, and tritons is shown as a function of the scaled rapidity, $\tilde{Y}$. The solid lines represent linear fits over the range $-0.1 \leq \tilde{Y} \leq 0.45$.

the PLF-TLF axis. This would result in a negative slope of the $<\tilde{p}_x>$. If the formation of the fragment occurs at a later time, where the PLF-TLF proximity is decreased, then it is possible for a more aligned emission to occur (right side of Fig. 2). Particles following the trajectory of the PLF would produce a positive slope value or PLF-flow.

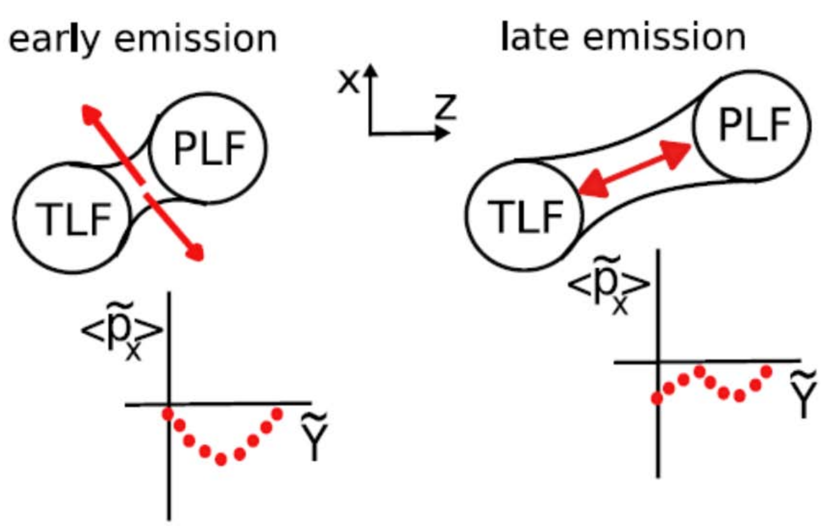

FIG. 2. Simple illustration demonstrating the proposed PLF-TLF proximity effect on the mid-rapidity fragments. The left side depicts the mechanism producing negative slopes due to an early emission of fragments. The right side shows a later emission of mid-rapidity fragments producing a positive slope.

The results suggest that on average tritons, ^{6}He, ^{8}He, and Z=3-4 fragments are emitted relatively early in the mid-rapidity region followed by deuterons and ^{3}He fragments. Protons and alpha, on average, are emitted last in comparison to the other fragments. These results are particularly interesting in the context of current research on the mid-rapidity, or neck, region which have observed increased IMF and n-rich fragment production in the neck region relative to the PLF region [1].

The validity of the method for determining the average order of emission was examined in the context of a Coulomb trajectory calculation and the classical molecular dynamics simulation [2]. The results demonstrated that the proximity of the PLF-TLF, or time of emission, has a direct connection to the observed PLF-Flow. The statistical multifragmentation model (SMM) [3] demonstrated that the observed average emission order is likely due to proximity of the second source which modifies the Coulomb energy of the system during the fragmentation. Lastly, the average emission order of the LCPs and IMFs was extracted from the antisymmetrized molecular dynamics (AMD) [4] and constrained molecular dynamics CoMD [5] simulations and showed good agreement with the experimentally determined mid-rapidity emission order.

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