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SHADOWING EFFECTS AND TRANSVERSE MOMENTUM DEPENDENCE OF PARTICLE EMISSION IN INTERMEDIATE ENERGY HEAVY ION COLLISIONS

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Abstract

Light particle emission was studied at GANIL for $^{36}\text{Ar} + ^{27}\text{Al}$ between 55 and 95 MeV/u and for $^{64}\text{Zn} + ^{58}\text{Ni}$ between 35 and 79 MeV/u. The correlation of these particles with the reaction plane was analyzed. In intermediate impact parameter events, the transverse momentum dependence of this correlation changes drastically with the energy for midrapidity particles. For both systems, at the upper incident energies, particles with highest transverse momenta are preferentially emitted perpendicular to the reaction plane. This can be qualitatively reproduced by simulations taking into account shadowing effects.

One of the basic motivations to study intermediate energy heavy ion collisions is the fact that the interaction changes from attractive to repulsive in this energy domain. Experimentally, one of the ways in which this change of dynamics manifests itself is the change of the azimuthal distribution relative to the reaction plane, for the emitted participant (midrapidity) particles.

At incident energies up to a few tens of MeV/u the interaction is dominated by the attractive mean field, giving rise to a deflection of the emitted particles to negative angles [1]. This attraction possibly initiates a collective rotation of the nuclear system: the azimuthal distribution for midrapidity particles peaks in the reaction plane at 0° and 180° , which could be described in terms of statistical emission from a hot rotating composite system [2]. This type of emission was called rotation-like effect [3]. It was studied as a function of energy, impact parameter and emitted particle mass in the collisions of $^{36}\text{Ar} + ^{27}\text{Al}$ from 36 to 95 MeV/u [4,5]. It was shown that this in-plane enhancement increases with the impact parameter and decreases with the incident energy.

In contrast, at higher incident energies (few hundreds of MeV/u), where the repulsive nucleon-nucleon collisions dominate, the azimuthal distributions exhibit maxima at angles perpendicular to the reaction plane. This anisotropy is due to collective effects such as squeeze-out [6,7].

Recently, experimental evidence was reported [8,5] in the $^{64}\text{Zn} + ^{58}\text{Ni}$ system between 35 and 79 MeV/u, for a transition from in-plane emission at low energy to out-of-plane (squeeze-out) emission at high energy. For $^{36}\text{Ar} + ^{27}\text{Al}$, on the contrary, an in-plane enhancement is noticed up to 95 MeV/u.

In order to get a better insight into these phenomena and to find a possible explanation for this behaviour we report here on transverse momentum dependence of particle emission at mid-rapidity for these two systems.

The experiments were performed at the GANIL facility in the NAUTILUS reaction chamber. In a nearly 4π geometry the multidetectors MUR [9] and TONNEAU [10] measured the velocities of charged products and identified their charge up to $Z=8$. In the $^{64}\text{Zn} + ^{58}\text{Ni}$ experiment, seven large solid angles silicon detectors were installed at polar angles between 3° and 30° and allowed to measure the energy and charge of products from $Z=3$ to $Z=30$. The selection of well characterized events was accomplished by using the sum of parallel momenta of all detected particles. These events were sorted as a function of the violence of the collision using the total transverse momentum to estimate the impact parameter b_{exp} [11]. The reaction plane was determined via transverse momentum analysis [12]. The polar axis used to build the azimuthal distributions was the beam axis.

Fig. 1 shows the azimuthal distribution for $Z=1$ and $Z=2$, midrapidity particles. The relative rapidity, $Y_r = Y/Y_{beam}$ is defined in the laboratory, thus midrapidity means $Y_r \approx 0.5$. The continuous line is a fit with the function : $dN/d\varphi = a_0(1 + a_1\cos\varphi + a_2\cos2\varphi)$.

In this formula a_1 corresponds to in-plane flow and is zero at midrapidity. The anisotropy factor a_2 is related to the ratio of out-of-plane to in-plane yields :

$$R_N = \frac{dN/d\varphi(90^\circ) + dN/d\varphi(-90^\circ)}{dN/d\varphi(0^\circ) + dN/d\varphi(180^\circ)} \quad \text{i.e.} \quad R_N = \frac{1 - a_2}{1 + a_2} \quad (1)$$

R_N is less than 1 for in-plane enhancement, equal to 1 for isotropic distributions and greater than 1 for squeeze-out (out-of-plane enhancement). The transverse momentum dependence of R_N for $Z=1$ particles coming from mid-peripheral $^{36}\text{Ar} + ^{27}\text{Al}$ reactions is shown in Fig. 2a. The relative transverse momentum of each particle with mass A is $P_T^{(0)} = (P_T/A)/(P_{beam}^{cm}/A_{beam})$. In Fig. 2a an in-plane enhancement ($R_N < 1$) is noticed for the three energies at all transverse momenta (except for the highest transverse momenta at 95 MeV/u where a slight out-of-plane enhancement can be noticed). But the pattern of $R_N(P_T^{(0)})$ changes dramatically with the incident energy. For 55 MeV/u an increase of in-plane enhancement with $P_T^{(0)}$ is noticed, whereas this in-plane enhancement diminishes with incident energy and the azimuthal distributions evolve to symmetry ($R_N = 1$) for the highest transverse momenta.

A similar behaviour is seen in Fig. 2b for the $^{64}\text{Zn} + ^{58}\text{Ni}$ system. At 49 MeV/u the in-plane enhancement increases with $P_T^{(0)}$. At 69 MeV/u the distributions are almost symmetric ($R_N \approx 1$). But at 79 MeV/u an out-of-plane enhancement is seen which increases with the transverse momentum.

This change of pattern with the incident energy for both systems could suggest a change of collision dynamics. However, other phenomena such as shadowing could induce similar

effects. Indeed, shadowing means some slowing down and even absorption for particles emitted in the direction of projectile and target spectators. The particles emitted perpendicular to the reaction plane will be less affected. This will distort the primary momentum distribution of the emitted particles. For example, starting from a primary uniform distribution, the particles with the highest transverse momenta will be detected preferentially perpendicular to the reaction plane because in this direction there is no stopping. Of course, if the spectators are small the stopping in the reaction plane may be negligible (at least for the highest transverse momenta) so finally we get the same uniform distribution. The same may happen in case of a strong in-plane enhancement: if the stopping is not effective or if the shadowed angle is small the detected particles will show an in-plane enhancement perhaps reduced, but still present at all transverse momenta.

In order to get more quantitative estimates we have made a simulation, the main ideas of which will be briefly outlined below.

For each event a primary momentum distribution of a rotation-like type is generated by flattening a Gaussian momentum distribution into an oblate shape of width σ , where

$$\sigma_x = \sigma_z > \sigma_y \quad (2)$$

Here the z axis points in the beam direction, the x axis is in the reaction plane and the y axis is perpendicular to the reaction plane. Fig. 3 shows $R_N(P_T^{(0)})$ at midrapidity for three such distributions. All three distributions show an in-plane enhancement which increases with transverse momentum. The shown values for σ_x , σ_y , and σ_z are given in MeV/c.

Then, the shadowing was simulated, following an idea from [13]. For a given impact parameter and for each emitted particle in an event, one generates a position inside the maximum zone of superposition of the two nuclei, assumed of spherical shape. According to the direction of its momentum, one determines the range of the emitted particle through the nuclear medium, which is compared to the mean free path λ . Finally, to simulate the slowing down, one considers that, after travelling the distance λ through the nuclear medium the transverse momentum is diminished by a ratio r_s .

For the primary momentum distributions from Fig. 3, in Fig. 4 are shown the corresponding $R_N(P_T^{(0)})$ distributions at midrapidity for two symmetric systems, taking into account the shadowing. The two corresponding ions have a radius r close to those of our studied systems. As in the experiment, $b/b_{max}=0.5$. For these simulations the mean free path λ was taken equal to 2 fm and the ratio r_s equal to 0.9.

A close similarity can be noticed between the simulations in Fig. 4 and the experimental results in Fig. 2. In agreement with the shadowing scenario above, we see an increase of R_N with $P_T^{(0)}$ (a reduction of the in-plane emission) for higher energies and even an out-of-plane enhancement for the higher $P_T^{(0)}$. The effect is more pronounced for $^{64}\text{Zn} + ^{58}\text{Ni}$, because, for the same relative impact parameter the shadow is larger for this system.

According to these simulations, the same mechanism for enhanced particle emission in the reaction plane is present for both systems, at all studied energies. The particularities of the

transverse momentum dependence in Fig. 2 could be explained by the increasing role of the nuclear shadowing as the in-plane enhancement due to rotation diminishes with the incident energy

In conclusion , the correlation of midrapidity particles with respect to the reaction plane was analysed for $^{36}\text{Ar} + ^{27}\text{Al}$ and $^{64}\text{Zn} + ^{58}\text{Ni}$ in a broad range of incident energies . The transverse momentum dependence of this correlation changes very much with the incident energy for intermediate impact parameter events . At the upper incident energies, particles with the highest transverse momenta are preferentially emitted perpendicular to the reaction plane . The effect is more pronounced for $^{64}\text{Zn} + ^{58}\text{Ni}$. Qualitatively, these features can be explained by an interplay between the nuclear shadowing for particles emitted in the direction of the reaction plane, and the decrease of this enhanced emission with the incident energy .

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Figure 1

Azimuthal distributions for mid-rapidity ($Y_r = 0.4 - 0.6$) $Z=1$ (a) and $Z=2$ (b) particles in $^{36}\text{Ar} + ^{27}\text{Al}$ at 55 MeV/u at intermediate impact parameter ($b_{\text{exp}}/b_{\text{max}} \approx 0.5$)

Figure 2

Out-of-plane/In-plane ratios as a function of transverse momentum for mid-rapidity ($Y_r = 0.4 - 0.6$), $Z=1$ particles for intermediate impact parameter, ($b_{exp}/b_{max} \approx 0.5$)

Figure 3

Simulated Out-of-plane/In-plane ratios as a function of transverse momentum for mid-rapidity particles from events having rotation-like momentum distributions (see text), without shadowing

Figure 4

Effect of shadowing on the Out-of-plane/In-plane ratios as a function of transverse momentum for mid-rapidity particles and intermediate impact parameter ($b/b_{max} = 0.5$). The simulation was made for two symmetric systems close to $^{36}\text{Ar} + ^{27}\text{Al}$ (a) and $^{64}\text{Zn} + ^{58}\text{Ni}$ (b). The primary momentum distributions are those of Fig. 3.