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Collective flow in Ar + KCl at 1.8 GeV/nucleon

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The failure of the standard sphericity tensor analysis to detect any significant collective flow effect in Ar+KCl at $1.8A$ GeV is examined in light of the success of the transverse momentum analysis technique suggested by Danielewicz and Odyniec in exhibiting collective flow in the same system. It is argued, using a simple estimate which takes into consideration the main features of the data, that the failure of the sphericity analysis is attributable to the dominant contribution of the longitudinal momentum of the spectators which has nothing to do with the collective effects for which sphericity analysis is designed. The exclusion of the spectators from the sphericity tensor leads to a clear signal from the collective transverse flow of the participants whenever such a flow takes place.

Sphericity analysis[1,2] has been employed successfully to detect collective flow effects in intermediate energy heavy ion central collisions, e.g., in the exclusive experiment ^{93}Nb + ^{93}Nb at 400 MeV/nucleon (Ref. 3) carried out at the Bevalac with the use of the plastic ball 4π detector. Definite evidence was found from this analysis for a sideways flow of nuclear matter (the side-splash effect) originating in the participant region. Another collective effect was also seen in this reaction: the bounceoff of the spectators with an average transverse momentum of 50 MeV/c per nucleon in the reaction plane (original state of the collision). On the other hand, a similar analysis of the semiexclusive data of the reaction Ar + KCl at 1.8 GeV/nucleon (Ref. 4) failed to detect any significant collective effect. More recently however, Danielewicz and Odyniec[5] introduced a novel transverse momentum technique that they used successfully to detect and exhibit collective flow in the last reaction. The present work is an attempt to understand the reason for this apparent failure of sphericity analysis for Ar + KCl and to consider modifications that will allow it to detect collective flow in such cases.

Sphericity analysis[1,2] involves calculating for each event of multiplicity M the tensor

$$F_{ij}=\sum_{\nu=1}^{M} P_i(\nu)P_j(\nu)W(\nu) , \tag{1}$$

where $P_i(\nu)$ is the ith Cartesian component of the momentum of fragment ν in the center of mass reference frame. In this paper the usual choice for the weight $W(\nu)=1/2M(\nu)$ is used, where $M(\nu)$ is the mass of the fragment. With this choice of $W(\nu)$, F_{ij} is often called the kinetic energy flow tensor. Collective flow is indicated by the existence of a nonzero flow angle (θ_F), which is the angle between the main axis of the tensor F_{ij} and the beam direction. Collective flow is thus related to the existence of nondiagonal elements of the sphericity tensor.

Danielewicz and Odyniec[5] introduced the weighted sum of the transverse momenta of the fragments for each event:

$$\mathbf{Q}=\sum_{\nu=1}^{M} w(\nu)\mathbf{P}_\perp(\nu) , \tag{2}$$

where the weight $w(\nu)$ depends on the rapidity y_ν of the fragment:

$$w(\nu)=\begin{cases} +1 \text{ for baryons with } y_\nu > y_c+\delta \\ -1 \text{ for baryons with } y_\nu < y_c-\delta \\ 0 \text{ otherwise} . \end{cases} \tag{3}$$

Here y_c is the center of mass rapidity. They choose $\delta=0.3$ to exclude particles from midrapidity which introduce unwanted fluctuations but do not contribute to the determination of the reaction plane. From the Ar + KCl data for central collisions corresponding to an impact parameter $b<2.4$ fm, they find

$$Q^2-\sum_\nu w(\nu)^2P_\perp(\nu)^2=4.7\pm0.5 \text{ (GeV}/c)^2 \tag{4}$$

rather than zero as expected if there were no collective effects. From this, they estimate that the average magnitude of the transverse momentum in the reaction plane imparted to a nucleon with $w(\nu)\neq0$ is 95 ± 5 MeV/c. The number of nucleons included in the summation for $\mathbf{Q}$ is about 46, which is about twice the total number of target and projectile spectators; the latter can be estimated from the approximate formula given in Ref. 6 to be ≈ 22 nucleons for an impact parameter of 2 fm. This indicates that at least half of the nucleons that contribute to the collective effect detected by this novel technique are participants. It must be noted, however, that this collective effect is closer to the bounceoff effect seen in Nb + Nb rather than the side-splash (except that in Nb + Nb the bounceoff is confined mainly to the spectators). This transverse momentum analysis technique will not therefore be able to detect a possible "side splash" coming from midrapidity particles due to compression effects in the heart of the participant region. Particles from midrapidity are found to have an average of zero transverse momentum in the reaction plane,[5] indicating a possible side-splash effect with azimuthal symmetry about the beam direction rather than a collective effect confined to the reaction plane. Such a side splash should be readily detected in a sphericity analysis.

To understand the failure of the sphericity analysis to detect such an effect in Ar + KCl at 1.8 GeV, let us consider the following scenario which takes into consideration the main features of the data. This scenario will help to illustrate some of the points that the present work emphasizes, it being understood that the final say in the matter must come from a careful analysis of the full data. We consider the symmetric system ^{40}Ca + ^{40}Ca rather than Ar + KCl in order to simplify the calculation. The projectile nucleons are divided into three categories: the spectators, the high rapidity participants, and the midrapidity participants whose momenta are denoted by $\mathbf{S}(\nu)$, $\mathbf{T}(\nu)$, and $\mathbf{P}(\nu)$, respectively (with a similar division for the target nucleons). In light of the results of Ref. 5 the number of participants with high rapidity is taken to be equal to the number of spectators ($\approx 0.27A$ at $b=2$ fm). The z axis is chosen along the beam direction and the reaction plane is taken to be the xz plane. The transverse momentum of each nucleon, for example, $\mathbf{S}_\perp(\nu)$ for a spectator, is divided into a component in the reaction plane, $\mathbf{S}_x(\nu)=S_x(\nu)\hat{\mathbf{i}}$, and a component, $\mathbf{S}_r(\nu)$, that has a random direction (corresponding to azimuthal symmetry around the beam direction):

$$\mathbf{S}(\nu)=\mathbf{S}_z(\nu)+\mathbf{S}_\perp(\nu)=\mathbf{S}_z(\nu)+\mathbf{S}_x(\nu)+\mathbf{S}_r(\nu)\ ,\qquad \langle \mathbf{S}_r(\nu)\rangle=0 \tag{5}$$

with similar divisions for the momenta of the participants $\mathbf{T}(\nu)$ and $\mathbf{P}(\nu)$. The spectators are assumed to continue with essentially the beam momentum: $\bar{S}_z\approx 900$ MeV/c, while $\bar{T}_z$ is taken to be ≈ 600 MeV/c. This implies that $\bar{P}_z\approx 240$ MeV/c, since from the data[4] we have that the average magnitude of the longitudinal momentum is ≈ 516 MeV/c per nucleon for $b=2$ fm. The corresponding value for the transverse component is 450 MeV/c. The results of the analysis in Ref. 5 motivate the choice

$$\bar{S}_x=\bar{T}_x=100\ \text{MeV}/c,\quad \bar{P}_x=0\ . \tag{6}$$

We also assign the values of the random components:

$$\overline{|S_r|}=100\ \text{MeV}/c,\quad \overline{|T_r|}=200\ \text{MeV}/c\ ,\qquad \overline{|P_r|}=770\ \text{MeV}/c\ , \tag{7}$$

where the only constraint has been to ensure that the average magnitude of the transverse momentum is ~ 450 MeV/c.

The kinetic energy flow tensor (per nucleon) corresponding to the above scenario, assuming complete symmetry between the target and projectile fragments, can then be written as follows:

$$\begin{aligned}
F_{zz}&=\frac{\alpha}{2m}(\bar{S}_z^2+\bar{T}_z^2)+\frac{(1-2\alpha)}{2m}\bar{P}_z^2\ ,\\
F_{xx}&=\frac{\alpha}{2m}(\bar{S}_x^2+\tfrac{1}{2}\overline{|S_r|}^2+\bar{T}_x^2+\tfrac{1}{2}\overline{|T_r|}^2)+\frac{(1-2\alpha)}{2m}(\bar{P}_x^2+\overline{|P_r|}^2/2)\ ,\\
F_{xz}&=F_{zx}=\frac{\alpha}{2m}(\bar{S}_z\bar{S}_x+\bar{T}_z\bar{T}_x)+\frac{(1-2\alpha)}{2m}\bar{P}_z\bar{P}_x\ ,\\
F_{yy}&=\frac{\alpha}{4m}(\overline{|S_r|}^2+\overline{|T_r|}^2)+\frac{(1-2\alpha)}{4m}\overline{|P_r|}^2\ ,\\
F_{yz}&=F_{zy}=0,\quad F_{yx}=F_{xy}=0\ ,
\end{aligned} \tag{8}$$

where we have neglected fluctuations in the momenta within each category. Here α is the ratio of spectators to the total number of nucleons and m is the nucleon mass. We notice that F_{ij} is already diagonal along the y axis so that we need only to diagonalize the x-z components. Using the values mentioned above [Eqs. (6) and (7) and the discussion preceding them] we get for ^{40}Ca + ^{40}Ca at $1.8A$ GeV and an impact parameter of 2 fm:

$$\begin{aligned}
F_{zz}&=117.2+52.1+14.0=183.3\ \text{MeV}\ ,\\
F_{xx}&=2.2+4.3+71.9=78.4\ \text{MeV}\ ,\\
F_{xz}&=F_{zx}=13.0+8.7+0=21.7\ \text{MeV}\ .
\end{aligned} \tag{9}$$

The three contributions to each term come from $\mathbf{S}(\nu)$, $\mathbf{T}(\nu)$, and $\mathbf{P}(\nu)$, respectively. This will yield a flow angle of 11° which is close to that determined from the data. Such a small flow angle for the impact parameter with the maximum weight is, however, not significant because of finite multiplicity effects that tend to yield a finite flow angle even if the momentum distribution is spherically symmetric.[7] Examining the tensor components in Eq. (9) indicates, however, that the value of the flow angle is determined essentially by the large contribution to F_{zz} coming from the longitudinal momentum of the spectators. This occurs because of the small size of the nuclei concerned so that for $b=2$ fm the number of spectators is relatively large ($\sim 27\%$ for ^{40}Ca + ^{40}Ca as compared to less than 20% for Nb + Nb) and because the experiment is carried out at a high energy (1.8 GeV/nucleon). Since the spectators have little to do with the compression effects that lead to the side splash of the participants for which the sphericity analysis is designed, it is obvious that their inclusion serves only to mask the real effect, namely, the large contribution to F_{xx} provided by the transverse momentum of the midrapidity participants. If, on the other hand, we exclude the contribution of the spectators when evaluating the tensor F_{ij} we get

$$F_{zz}=66.1,\quad F_{xx}=76.2,\quad F_{xz}=F_{zx}=8.7\ \text{MeV}\ , \tag{10}$$

which yields a much larger flow angle $\theta_F\approx 49°$.

We, therefore, propose that the Ar + KCl data be analyzed again with the spectators excluded in evaluating the kinetic flow tensor. Such a procedure must be followed whenever the reaction involves a light system and/or whenever the experiment is carried out at relatively high energies. It may also turn out to be important in other situations. The only drawback associated with excluding the spectators is the decrease in the number of fragments that contribute to the sphericity tensor which may lead to an increase in the finite-multiplicity distortions of the flow characteristics of the given event.[7] This, however, may be partly compensated for by first determining the reaction plane for each event in a manner free from finite-multiplicity distortions as in Ref. 5 and then carrying out the sphericity analysis in the coordinate system connected with the reaction plane. The method of Danielewicz and Odyniec and the method suggested in the present work therefore complement each other as they probe different aspects of collective flow.

The exclusion of the spectators from the kinetic flow tensor is most easily carried out by excluding fragments whose longitudinal momenta (per nucleon) exceed a certain value $\widetilde{P}_z$, or by excluding fragments whose transverse momenta (per nucleon) are less than a certain value $\widetilde{P}_\perp$, or by a combination of the two conditions. This amounts to making the weight $W(\nu)$ in Eq. (1) momentum dependent. As a rough guide the number of particles excluded must be comparable to what is expected from the geometric formula given in Ref. 6 for the number of spectators. In any case, this procedure is meaningful only if the results of the analysis (e.g., θ_F) are not too sensitive to the particular values of $\widetilde{P}_z$ and/or $\widetilde{P}_\perp$ used. This criterion can be used to define optimal value(s) for $\widetilde{P}_z$ and/or $\widetilde{P}_\perp$ at which, for instance, $|\partial\theta_F/\partial\widetilde{P}_z|$ and $|\partial\theta_F/\partial\widetilde{P}_\perp|$ are minimized. The degree of success of this procedure, however, can be determined only by the analysis of the actual event-by-event data.

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