Azimuthal Anisotropy of $\eta$ and $\pi^0$ Mesons in Heavy-Ion Collisions at 2 AGeV

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Significant compression of nuclear matter achieved during relativistic heavy-ion collisions manifests itself in anisotropies of observed azimuthal distributions of baryons emerging from the collisions. In-plane emission of baryons in the direction of projectile-like (forward hemisphere) or target-like (backward hemisphere) spectator nucleons is designated as positive directed flow, while out-of-plane emission of baryons at midrapidity is designated as negative elliptic flow, see [3]. Similar to baryons, negative elliptic flow was observed for high transverse momentum neutral and charged pions emitted at midrapidity in 1 AGeV Au+Au collisions at SIS (GSI) [3,4]. In contrast to positive directed flow of baryons, directed flow of charged pions was found to be negative [3]. The origin of these anisotropies has not been attributed to the expansion of nuclear matter, rather to the final state interactions of pions with the spectator matter transiently concentrated in the reaction plane [3-4]. Therefore, an increase in the magnitude of elliptic flow of pions with increasing size of spectator matter was predicted [3-4]. However, recent detailed study of elliptic flow of charged pions in Bi+Bi collisions at 0.4-1.0 AGeV reports a very small variation of its magnitude with the change of the number of spectator nucleons, see [3-4]. Hence, the origin of the observed azimuthal anisotropies of pions is still unclear.

While the main source of pions in relativistic heavy-ion collisions is the decay of $\Delta(1232)$ resonances, $\eta$ mesons are produced mainly by the decay of $N^*(1535)$ resonances. The absorption of pions in hot nuclear matter proceeds via the $\Delta(1232)$ resonance which decays dominantly by pion emission. However, only about 50% of all $N^*(1535)$ resonances created by $\eta$-meson absorption will reemit $\eta$ mesons. Therefore, a comparison of the $\eta$- and $\pi^0$ azimuthal anisotropy may yield information on the propagation of these mesons, as well as on the dynamics of the parent baryon resonances.

Below we present results of the first experimental study of azimuthal distributions of $\eta$ mesons emitted in collisions of 1.9 AGeV $^{58}$Ni+$^{58}$Ni and 2 AGeV $^{40}$Ca+$^{nat}$Ca nuclei, and compare them with azimuthal distributions of $\pi^0$ mesons in the same colliding systems. The experiments were performed at the Heavy-Ion Synchrotron SIS at GSI Darmstadt.

In the first experiment a 1.9 AGeV $^{58}$Ni beam with an intensity of $6.5 \times 10^6$ particles per spill (spill duration 8 s and repetition rate 15 s) was incident on a $^{58}$Ni target (502 mg/cm$^2$). In the second experiment, a $^{nat}$Ca target (320 mg/cm$^2$) was bombarded by a $^{40}$Ca beam with kinetic energy 2 AGeV and an intensity of $5 \times 10^6$ particles per spill (spill duration 10 s and repetition rate 14 s). Photon pairs from the neutral-meson decay were detected in the Two-Arm Photon Spectrometer (TAPS) [4]. This detector system consisted of 384 BaF$_2$ scintillators arranged in 6 blocks of 64 modules with individual Charged Particle Veto detectors (CPV) in front of each module. The blocks were mounted in two towers positioned at 40$^\circ$ with respect to the beam direction at the distance of 150 cm. Three blocks were positioned in each tower at +21$^\circ$, 0$^\circ$ and -21$^\circ$ with respect to the horizontal plane. In this setup, only neutral mesons around mid-rapidity $y_{nm}$ were detected. The geometrical acceptance of TAPS for the $\pi^0$ and $\eta$ detection was of an order 1 $\times 10^{-3}$. 

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The reaction centrality was determined by the hit multiplicity of charged particles ($M_{\text{react}}$) in a reaction detector. This detector, comprising 40 small plastic scintillators, was positioned close to the target and covered the polar angles from $14^\circ$ to $30^\circ$. Most of the particles emitted in this angular range are participant nucleons [10]. The plastic Forward Wall (FW) of the KaoS collaboration, see [1], comprising 320 plastic scintillators was positioned 520 cm downstream of the target and covered the polar angles from 0.7$^\circ$ to 10.5$^\circ$. Particles emitted in this angular range are predominantly projectile-like spectator nucleons bounced off in the reaction plane [1]. The FW provided the information on emission angle, charge and time-of-flight of protons and light charged fragments up to Z=8.

The total charge $Z_{FW}$ of particles detected by the FW allowed us to estimate the average number of projectile-like spectators $\langle A_{sp}\rangle$ for each studied bin in multiplicity $M_{\text{react}}$, determined by the reaction detector. We used the relation $\langle A_{sp}\rangle = (Z_{FW}) A_{\text{proj}} / Z_{\text{proj}}$, where $A_{\text{proj}}$ and $Z_{\text{proj}}$ are mass and charge of the projectile, respectively. The resulting distributions of the total charge $Z_{FW}$ for studied bins in $M_{\text{react}}$ are shown in the left column of Fig.1, both for the Ni+Ni and Ca+Ca collisions. The systematic error of the values $\langle A_{sp}\rangle$ was found to be less than 4 units, see [12].

The reaction plane for each event was defined by the incident beam direction and the vector

$$\vec{Q} = \sum_{i=1}^{n} Z_i \vec{x}_i / | \vec{x}_i | ,$$

where the sum runs over all n particles detected by the FW in the event. $\vec{x}_i$ is the position vector of particle i in the x-y plane in the FW and $Z_i$ is its charge. The unbiased azimuthal-angle distribution of the vector $\vec{Q}$ was found to be flat after introducing a correction, which takes into account the shift of the beam position with respect to the geometrical center of the FW. The required corrections were below 1 cm.

Because of finite multiplicity fluctuations, the azimuthal angle $\phi$ of the vector $\vec{Q}$ can differ from the azimuthal angle of the true reaction plane $\phi_{\text{true}}$ by a deviation $\Delta \phi_{pl}$. To estimate the width $\sigma_{pl}$ of the distribution $N(\Delta \phi_{pl})$ we randomly divided the hits in each event into two subgroups containing each one half of the number of particles, see [13]. For each subevent one can construct two independent vectors $\vec{Q}_1$ and $\vec{Q}_2$, according to Eq.(1) and extract the angle $\Delta \phi_{12}=\phi_1 - \phi_2$ between the two vectors. The width $\sigma_{12}$ of the resulting distribution $N(\Delta \phi_{12})$ is a measure of the precision of the reaction-plane determination. In the approximation of a Gaussian distribution of $N(\Delta \phi_{pl})$ one has $\sigma_{pl} = \sigma_{12}/2$. Our analysis was restricted to a sufficient vector length $| \vec{Q} |$ in order to reject the most central events with no spectator flow. This selection removes 25% of all registered events. The resolution $\sigma_{pl}$ varies between 43$^\circ$ and 55$^\circ$ depending on the reaction centrality and the colliding system, see Table I. These values agree with published data from studies of charged-baryon flow in similar colliding systems [13-15]. Photon-particle discrimination has been performed in TAPS as described in [10]. For each pair of detected photons in a given event we calculated the invariant mass $M_{\text{pair}}$, and the momenta $\vec{p}_{\text{pair}}$ using the following relations: $M_{\text{pair}}^2 = 2E_1E_2(1 - \cos \Theta_{12})$ and $\vec{p}_{\text{pair}} = \vec{p}_1 + \vec{p}_2$, where $E_1$, $\vec{p}_1$ and $E_2$, $\vec{p}_2$ are the energies and momenta of the corresponding photons, $\Theta_{12}$ is the opening angle of the photon pair. We analyzed only neutral mesons in a narrow rapidity window ($|y - y_{cm}| \leq 0.1$). The combinatorial background, due to uncorrelated photon pairs, was deduced by the method of event mixing from experimental data, i.e. combining photons from different events with the same overall event characteristics [10,16]. The resolution in $M_{\text{pair}}$ was 15 MeV/$c^2$ and 45 MeV/$c^2$ (FWHM) for the $\pi^0$ and $\eta$ peaks, respectively [17].

We found that only the magnitude of the combinatorial background is dependent on the azimuthal angle $\Delta \phi = \phi_{\text{pair}} - \phi$ of meson emission relative to the reaction plane [1]. Therefore, the shape of the combinatorial background deduced by the method of event mixing for each bin in $M_{\text{react}}$ and transverse momenta $p_t$ of the photon pair was scaled to the experimental data for each bin in azimuthal angle $\Delta \phi$ separately and subtracted from the data. We present in Fig.1 the resulting azimuthal yields of $\eta$ mesons, soft $\pi^0$ (0$\leq p_t \leq 200$ MeV/$c$) and hard $\pi^0$ (600$\leq p_t \leq 800$ MeV/$c$) for different bins in $M_{\text{react}}$ for both systems studied.

We fitted the azimuthal yields of $\eta$ and $\pi^0$ mesons both by assuming a constant (isotropic distribution) and by the first two terms of a Fourier expansion in the azimuthal angle:

$$N(\Delta \varphi) = \frac{N_0}{2\pi} \left( 1 + 2v_1 \cos(\Delta \varphi) + 2v_2 \cos(2\Delta \varphi) \right) ,$$

which are used to parametrize the directed ($v_1$) and elliptic ($v_2$) flow [17]. The standard F-test rejects the fit of azimuthal yields of $\eta$ mesons by a constant with a confidence level of 95%. The extracted values of $v_1$ are zero within the error bars, as should be expected since we study symmetric colliding systems at midrapidity, see [13].

The resulting values of the parameter $v_2$ for $\eta$ and $\pi^0$ mesons are given in Table I. The parameter $v_2$ is negative for $\eta$ mesons, indicating a preferred emission perpendicular to the reaction plane (negative elliptic flow). In contrast to previous studies of heavy systems at 1 AGeV the elliptic-flow signal $v_2$ for $\pi^0$ mesons is pronounced in peripheral ($\langle A_{sp}\rangle = 51$) Ni+Ni collisions only.

The measured azimuthal distributions are affected by the resolution in the determination of the reaction plane.
FIG. 1. The left part shows the measured distribution of the total charge of particles detected in the FW for different bins in multiplicity M_{react} (see Table I): (a) - (c) for the experiment \( ^{58}\text{Ni}^+^{58}\text{Ni} \) at 1.9 AGeV and (d) - (e) for the experiment \( ^{40}\text{Ca}^+^{nat}\text{Ca} \) at 2 AGeV. The arrows indicate mean values of total charge. The right part shows the measured azimuthal angle distributions of \( \eta \) mesons, soft \( \pi^0 \) (0 \( \leq \) \( p_t \) \( \leq \) 200 MeV/c) and hard \( \pi^0 \) (600 \( \leq \) \( p_t \) \( \leq \) 800 MeV/c) with respect to the reaction plane which correspond to the same bins in reaction centrality (see left part of the picture). The horizontal error bars indicate the bin width.

Therefore, it is necessary to correct the \( v_2 \) coefficients for the fluctuation \( \Delta \phi_{pl} = \phi_{true} - \phi \) of the azimuthal angle of the estimated reaction plane with respect to the true one. Averaging over many events, one obtains the following relation between the measured \( v_2 \) coefficients and the true \( v_{true}^2 \) coefficients:

\[
v_{true}^2 = \frac{v^2}{\langle \cos^2 \Delta \phi_{pl} \rangle}
\]

with \( R = \exp(L/\lambda) \), where \( \lambda \) is the mean free path for mesons in cold spectator matter and \( L = 2 \cdot A_{sp}^{1/3} \) fm is the mean thickness of spectator matter. The mean free path in cold spectator matter for \( \eta \) mesons is \( \lambda_\eta \approx 1-2 \) fm for the momentum range \( p_\eta \approx 50-200 \) MeV/c [18,19], and for \( \pi^0 \) mesons \( \lambda_{\pi^0} \approx 1-6 \) fm [20]. The dash-dotted lines in Fig.2 present the results of these calculations for two different values of \( \lambda \): \( \lambda = 2 \) fm and \( \lambda = 6 \) fm. It is obvious, that the simple scenario assuming final-state interactions with spectators alone can not describe the strong difference between the \( \eta \) and \( \pi^0 \) azimuthal anisotropies. The observed dependence of the magnitude of the azimuthal anisotropy for \( \eta \) mesons on the number of spectator nucleons seems to contradict the model, too.

The \( \eta \) mesons are solely produced by the decay of the heavy N\(^*(1535)\) resonances which can only be excited in the early stage of the collision. Consequently, most of the

We calculate the parameter \( v_{true}^2 \) as function of the number of spectators \( A_{sp} \) from the equation

\[
v_{true}^2 = 0.5(1 - R)/(1 + R)
\]
η mesons are emitted after rescattering in the early phase of the collision, while most of the π⁰ mesons are emitted after the spectators have passed the collision zone. This may explain the much stronger azimuthal anisotropy observed for η mesons. However, for a quantitative explanation microscopic model calculations are needed.

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### TABLE I. Parameters \( v_2 \) (not corrected for the reaction-plane uncertainty) for π⁰ and η mesons deduced from the experimental azimuthal distributions for several intervals (a-e) in \( M_{\text{react}} \). Corresponding mean number of projectile-like spectators \( \langle A_{\text{sp}} \rangle \), uncertainty of the reaction plane angle \( \sigma_{\phi_{pl}} \), correction of \( v_2 \) due to this uncertainty are given (see text). For π⁰ mesons the selected intervals in transverse momentum \( p_t \) are indicated.

| Reaction | \( ^{58}\text{Ni}+^{58}\text{Ni} \) at 1.9 AGeV | \( ^{40}\text{Ca}+n\text{at} \) Ca at 2 AGeV |
|----------|--------------------------------|---------------------------------|
| \( M_{\text{react}} \) | \( \langle A_{\text{sp}} \rangle \) | (a) 2 - 6 | (b) 7 - 10 | (c) \( \geq 11 \) | (d) 1 - 3 | (e) \( \geq 4 \) |
| \( \langle A_{\text{sp}} \rangle \) | 51 | 44 | 37 | 34 | 28 |
| \( \sigma_{\phi_{pl}} \) [°] | 43 | 46 | 50 | 52 | 55 |
| \( \cos2\Delta\phi_{pl} \) | 0.37 | 0.32 | 0.26 | 0.22 | 0.19 |

\( v_2(\eta) \) \[ p_t \text{ MeV/c} \] \[ \begin{array}{l} 0 - 600 \text{-0.08±0.04} \\ 0 - 200 \text{-0.12±0.05} \\ 0 - 100 \text{-0.10±0.06} \\ 0 - 09±0.03 \\ 0 - 09±0.04 \end{array} \]

\( v_2(\pi^0) \) \[ p_t \text{ MeV/c} \] \[ \begin{array}{l} 0 - 600 \text{0.033±0.017} \\ 0 - 200 \text{0.021±0.019} \\ 0 - 100 \text{0.026±0.031} \\ 0 - 09±0.016 \\ 0 - 09±0.021 \end{array} \]