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# IMF-IMF azimuthal correlations as a tool to probe reaction dynamics in $^{36}$Ar + $^{48}$Ti at 45 $A$ MeV

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**Abstract**

IMF-IMF azimuthal correlation functions have been measured in $^{36}$Ar + $^{48}$Ti collisions at 45 $A$ MeV. The experimental data as well as the events generated with IQMD were sorted with respect to impact parameter and the analysis was restricted to the mid-rapidity region. We find strong anisotropies and asymmetries in the measured correlation functions, which cannot be described by independently emitted particles. The measured correlation functions are, however, well reproduced by IQMD model calculations, although decay of a small mid-rapidity source cannot be excluded experimentally. © 1998 Elsevier Science B.V. All rights reserved.

*Keywords:* IMF's; IQMD; Azimuthal correlations

Azimuthal correlations are a powerful tool to probe the dynamics of heavy-ion reactions, free from uncertainties in the reconstruction of the reaction plane [1–4]. In this Letter, this technique is applied to the $^{36}$Ar + $^{48}$Ti reaction at 45 $A$ MeV, to study rotational effects [1–4,9] as have been observed in azimuthal correlations between light particles. In our work we concentrate on Intermediate Mass Fragments (IMF's) with $Z = 3$–8.

The azimuthal correlation functions have been measured with the Huygens Detectors [5]. The Huygens Detectors, a central time-projection chamber (TPC) surrounded by a plastic scintillator barrel ($10° < \theta < 78°$) and four CsI(Tl) walls at backward angles ($121° < \theta < 177°$), are highly symmetric in the azimuthal angle $\phi$ and enable us to measure the azimuthal particle distribution with an accuracy of $\Delta\phi \approx 6°$. The TPC was operated at a pressure of 60 mbar (isobutane) leading to energy thresholds for the IMF's ranging from 3 $A$ MeV for $Z = 3$ to 4 $A$ MeV for $Z = 8$. Particle identification was obtained by the $E$ vs $dE$ technique. The $^{36}$Ar beam was accelerated at the GANIL facility, in Caen (France). In this experiment the Huygens Detectors were used in conjunction with the forward wall detector 'MUR' ($3° < \theta < 30°$) of LPC [11].

The azimuthal correlation function is defined as:

$$C(\Delta\phi) = \frac{N_{corr}(\Delta\phi)}{N_{uncorr}(\Delta\phi)}, \tag{1}$$

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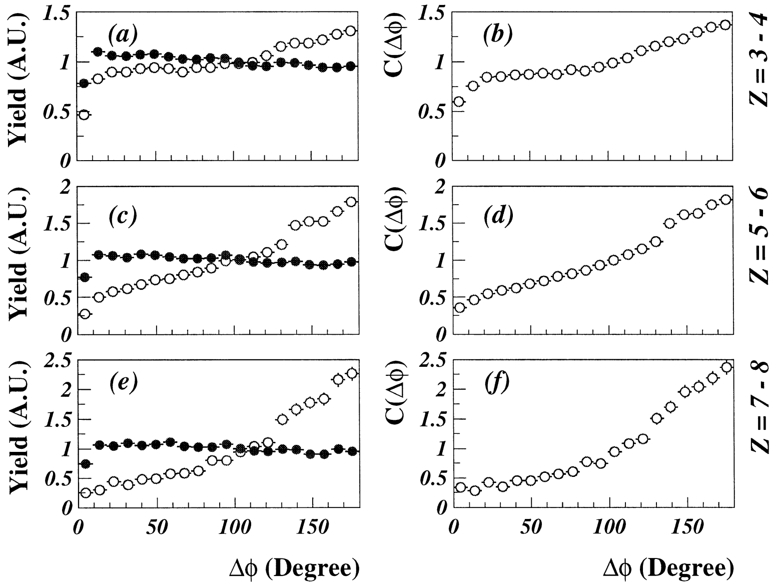


Fig. 1. IMF-IMF azimuthal correlation functions for mid-central events. Correlation functions are shown for differently charged IMF's (left-hand side). The open circles are the data points and the solid circles represent results from event mixing. On the right-hand side the resulting azimuthal correlation is shown (the measured azimuthal correlation divided by the azimuthal correlation function obtained by event mixing).

where $\Delta\phi$ is the relative azimuthal angle between the two particles, $N_{corr}(\Delta\phi)$ the distribution of coincident fragment pairs and $N_{uncorr}(\Delta\phi)$ the distribution of fragment pairs obtained by mixing particles from different events with the same fragment distribution and total event multiplicity. The same fragment distribution is defined as the same number of fragments per charge bin.

The experimental data analyzed in this Letter were sorted with respect to impact parameter. Three different impact parameter classes were defined: peripheral, mid-central and central. The different impact parameter classes were deduced from the charged particle multiplicity ($N_c$) measured by the Huygens Detectors and the 'MUR', under the assumption that the charged particle multiplicity depends monotonically upon impact parameter [5–7]. Using the method described in Refs. [6,7], we define $b/b_{max} > 0.7$ as peripheral, $b/b_{max} < 0.35$ as central and the region in between as mid-central. Moreover, the analysis is restricted to the mid-rapidity region, defined as the region where $|v_{zcm}| < 0.07c$. For this system, the center of mass velocity is 0.13 c and the beam velocity is 0.3 c.

Fig. 1 shows the azimuthal correlation function at mid-rapidity for the mid-central events. In this figure we have divided the IMF's in three different groups: $Z = 3$–$4$, $Z = 5$–$6$ and $Z = 7$–$8$. On the left-hand side of Fig. 1 the IMF-IMF azimuthal correlation function is shown together with the corresponding azimuthal correlation functions obtained by event mixing. The latter gives only a correction at small values of $\Delta\phi$ due to the finite azimuthal position resolution of the detectors. The IMF-IMF correlation functions, which are obtained by dividing the measured data points by the data points obtained from event mixing, are shown on the right-hand side.

If the correlations are caused by independently emitted fragments, then the correlation function can be calculated using the convolution of the single particle azimuthal distributions. In this case the auto-correlation function is given by:

$$C(\Delta\phi) = \int_0^{2\pi} P(\phi) P(\phi + \Delta\phi)\, d\phi. \qquad (2)$$

The single particle azimuthal distribution can be parameterized by [1–3]:

$$P(\phi) \propto 1 + \alpha_1 \cos(\phi) + \alpha_2 \cos(2\phi), \qquad (3)$$

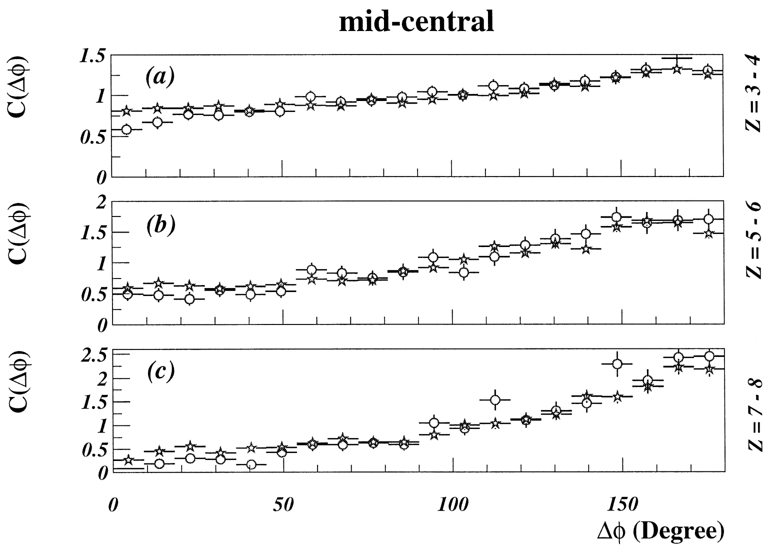


Fig. 2. IMF-IMF azimuthal correlation functions for mid-central events. Correlation functions are shown for a: $Z = 3$–4, b: $Z = 5$–6 and c: $Z = 7$–8. The open circles are IQMD data filtered by the detector set-up (GEANT). The open stars represent the unfiltered IQMD data. A comparison shows that the detector geometry and thresholds do not significantly modify the observed azimuthal correlation.

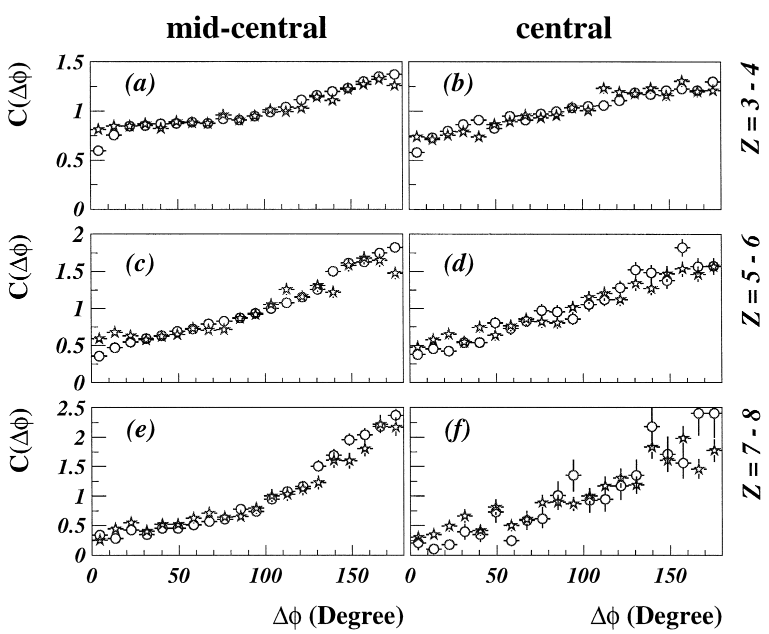


Fig. 3. IMF-IMF azimuthal correlation functions. Correlation functions are shown for differently charged IMF's. In the frames on the left-hand side the correlation functions are shown for the mid-central events, on the right-hand side the correlation functions for the central events are shown. The open stars represent the IQMD simulations and the open circles are the measured data points.

where the $\cos(\phi)$ term is interpreted in terms of a directed flow effect and the $\cos(2\phi)$ term is often used to describe rotational effects. Combining Eq. (3) and Eq. (2) leads to the following azimuthal correlation function:

$$C(\Delta\phi) \propto 1 + \lambda_1 \cos(\Delta\phi) + \lambda_2 \cos(2\Delta\phi), \tag{4}$$

with [9]:

$$\alpha_i = \sqrt{2\lambda_i}\,. \tag{5}$$

A motivation for the rotational term in Eq. (4) is derived in Ref. [10]. Here the thermal particle emission from a rotating source leads to an azimuthal correlation functions given, to order $\cos^2$, by:

$$C(\Delta\phi) \propto 1 + \lambda_2 \cos(2\Delta\phi) + \lambda_4 \cos^2(2\Delta\phi). \tag{6}$$

Fig. 1 clearly shows an enhancement at $\Delta\phi = 180°$ which cannot be explained by *independently* emitted fragments from a rotating source. Independently emitted fragments should give rise to an enhancement at $\Delta\phi = 0°$ which should be equal or stronger than the enhancement at $\Delta\phi = 180°$. Moreover, describing our azimuthal correlation function by Eq. (4) yields a negative value for $\lambda_1$, which implies an imaginary $\alpha_1$.

This enhancement could be due to momentum conservation in a mid-rapidity source. Therefore, the azimuthal correlations have been studied using a simple phase-space generator assuming a participant spectator behaviour for mid-central collisions. In order to describe the observed enhancement at $\Delta\phi = 180°$ (and especially the widths of this distribution) different source sizes had to be used for the different groups of IMF's. For the mid-central collisions and $Z = 3-4$ emission a source with a mass of 32 was able to reproduce the observed enhancement. For $Z = 5-6$ and $Z = 8$ the masses of the sources needed were 36 and 38, respectively.

For a more complete simulation IQMD [12,13] calculations have been performed, and 500.000 minimum bias events were generated. These events have been analyzed in the same way as the experimental data, including the cut on $v_{\mathrm{zcm}}$. GEANT [14] simulations were used to filter the IQMD results in order to calculate the influence of the detector geometry and energy thresholds on the observed azimuthal correlations. The detector did not significantly modify the observed correlation function (see Fig. 2), therefore, we have chosen to present the unfiltered IQMD calculations to be compared with the measured azimuthal correlation function.

In Fig. 3 the experimental and IQMD azimuthal correlation functions for the different IMF's are compared. The calculated correlation functions obtained for mid-central collisions are shown on the left-hand side and reproduce the experimental results. The correlation functions for the central events are given on the right-hand side. Once more, the experimental data are reproduced by IQMD. The comparison between the mid-central and central events shows that the azimuthal correlation function becomes less pronounced for central collisions.

The study of the azimuthal correlation function in the $^{84}$Kr + $^{197}$Au [8] system at 35, 55 and 70 *A* MeV, showed a similar enhancement at $\Delta\phi = 180°$. This enhancement was argued to be caused by Coulomb suppression at small relative angles, therefore, we have performed IQMD simulations for the $^{36}$Ar + $^{48}$Ti system without the Coulomb force. For our system it did not modify the azimuthal correlation functions for IMF's emitted at mid-rapidity.

In an effort to understand the observed enhancement at 180° and its dependence on the impact parameter we examined the azimuthal and polar particle distributions via IQMD calculations. Fig. 4a shows the azimuthal distribution of the IMF's with $Z = 3$–$4$ emitted at the mid-rapidity region. The azimuthal distribution is shown with respect to the event plane at $\phi = 0°$. This azimuthal particle distribution clearly shows the effect of in-plane flow. Fig. 4b gives the azimuthal correlation function obtained in the event-by-event analysis. The simulation shows, like in the data, an enhancement at $\Delta\phi = 180°$. The polar angle distribution in the center of mass of the $^{36}$Ar + $^{48}$Ti system of these IMF's is presented in Fig. 4c. Fig. 4c and calculations done by [15] using QMD lead to the conclusion that the origin of the IMF's, even at the mid-rapidity region, could be still projectile-like and target-like. The mass symmetry of the system will result in almost equal amounts of these target-like and projectile-like IMF's, which nicely explains the measured data. Such a scenario is discussed by Buta [3] for simulations with fixed distributions.

In order to examine this memory effect [15] (where IMF's even for small impact parameters and at the

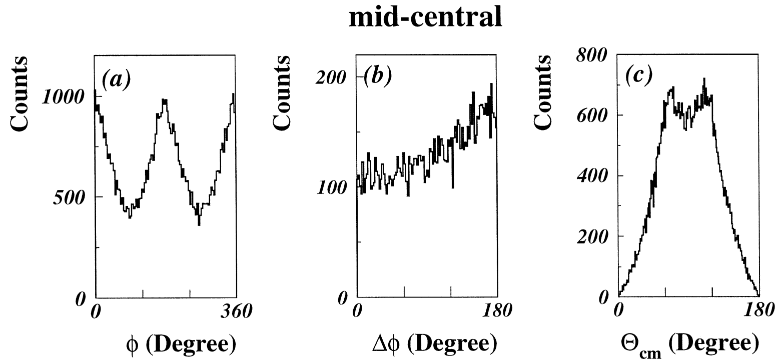


Fig. 4. IQMD simulations for mid-central impact parameters. a: azimuthal distribution for IMF's with $Z=3$ and 4 at the mid-rapidity region, where the event plane is located at $\phi=0°$. b: the resulting azimuthal correlation function (not normalized). c: polar angle in the center of mass for these IMF's.

mid-rapidity region still are projectile-like or target-like), we have made polar angle distributions as a function of the centrality of the collision and the charge of the IMF's. Fig. 5 shows the polar angle distributions for the different IMF's, where in the upper part the mid-central IQMD simulations are shown and in the lower part the central simulations. This figure shows that for the heavier IMF's this memory effect is stronger and, therefore, the azimuthal correlation function is stronger peaked at $\Delta\phi = 180°$. For central collisions this memory effect decreases slightly and the azimuthal correlation function becomes less pronounced.

In conclusion, IMF's produced in the $^{36}$Ar + $^{48}$Ti system at 45 $A$ MeV show a distinct azimuthal correlation that can not be explained by independently emitted fragments. However, the observed correlations are well reproduced by IQMD calcula-

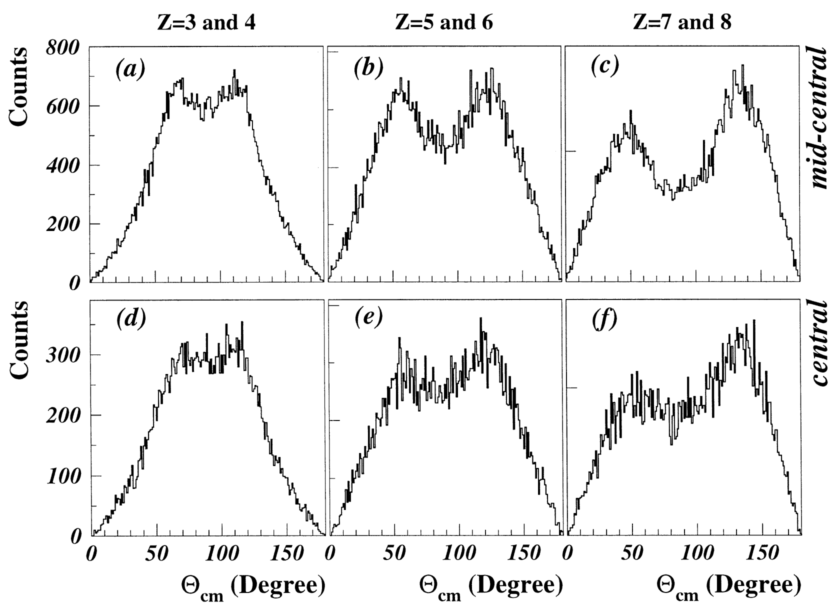


Fig. 5. IQMD simulations of the polar angle distributions for the different IMF's for mid-central and central collisions.

tions. Momentum conservation for a small mid-rapidity source can also lead to an azimuthal correlation function which has an enhancement at $\Delta\phi = 180°$ [2]. The calculated polar-angle distributions of the IMF's obtained with IQMD show the existence of projectile-like and target-like fragments at the mid-rapidity region for both mid-central and central collisions. This in combination with the mass symmetry of the system, leads to an azimuthal correlation between target-like and projectile-like IMF's that can explain nicely the observed enhancement at $\Delta\phi = 180°$.

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