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July 27, 2006

Physics Letters B

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d-α correlation functions and collective motion in Xe+Au collisions at E/A=50 MeV

G. Verde[1], P. Danielewicz[2], W.G. Lynch[2], C.F. Chan[2], C.K. Gelbke[2], L.K. Kwong[2], T.X. Liu[2], X.D. Liu[2], D. Seymour[2], R. Shomin[2], W.P. Tan[2a], M.B. Tsang[2], A.Wagner[2b], H.S. Xu[2c], D.A. Brown[3], B. Davin[4], Y. Larochelle[4d], R.T. de Souza[4e], R.J. Charity[5], and L.G. Sobotka[6]

[1] *Istituto Nazionale di Fisica Nuclear, Sezione di Catania, 64, Via Santa Sofia, 95123 Catania, Italy* and *GANIL, (DSM-CEA/IN2P3-CNRS), B.P. 5027, F-14076 Caen Cedex 5, France*

[2] *National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University*, East Lansing, *MI 48824, USA*

[3] *Department of Chemistry and IUCF, Indiana University, Bloomington, IN 47405, USA*,

[4] *Department of Chemistry, Washington University, St. Louis, MO 63130, USA*

Abstract

The interplay of the effects of geometry and collective motion on d-α correlation functions is investigated for central Xe+Au collisions at E/A=50 MeV. The data cannot be explained without collective motion, which could be partly along the beam axis. A semi-quantitative description of the data can be obtained using a Monte-Carlo model, where thermal emission is superimposed on collective motion. Both the emission volume and the competition between the thermal and collective motion influence significantly the shape of the correlation function, motivating new strategies for extending intensity interferometry studies to massive particles.

PACS: xxxxxx

Nuclear collisions provide the only means to study highly excited nuclear matter and its phase transitions under laboratory-controlled conditions. Such collisions produce highly excited nuclear systems that persist momentarily. Space-time information about the fate of these systems can be accessed through the dependence of two-particle correlation functions at low relative momentum on Boson or Fermion symmetries and on the particle mutual nuclear and Coulomb interactions [1-4]. Particularly successful investigations using proton-proton correlations at intermediate energies and pion-pion correlations at high energies have been performed in the last decades [1-8]. Extending these studies to all particle species produced during a reaction represents an important objective because different particles may originate at different stages of the reaction where the densities are different. Correlation functions between complex particles and heavy fragments may be more relevant than light particle correlation functions to stages of the reaction where multifragmentation and the liquid-gas phase transition are expected to occur [8-14]

Since thermal velocities decrease with particle mass, $v_{th} \propto (m)^{-1/2}$, while collective velocities do not depend on mass, the latter become increasingly important as more massive particles are considered [15]. This influences the connection between the space-time structures of the system and the measured correlations [15,16] for such particles. In this article, we study deuteron-alpha correlation functions measured in ^{129}Xe+^{197}Au collisions at E/A=50 MeV. We demonstrate that the correlation data can be understood only if one incorporates significant effects induced by collective motion and temperature along with the space-time geometry.

We studied central ^{129}Xe+^{197}Au collisions at E/A=50 MeV, using Au targets of 3 mg/cm^2 areal density and ^{129}Xe beams, having an intensity of about 10^8 pps, from the K1200 cyclotron of the National Superconducting Cyclotron Laboratory at Michigan State University. Isotopically resolved particles with $1 \leq Z \leq 10$ were detected with nine telescopes of the Large Area Silicon Strip Array (LASSA) [17,18]. Each telescope consisted of one 65 μm single-sided silicon strip detector, one 500 μm double-sided silicon strip detector and four 6-cm thick CsI(Tl) scintillators. The strips of the silicon detectors provided an angular resolution of about ±0.43°. The center of the LASSA device was located at a polar angle of θ=35° with respect to the beam axis, covering polar angles of $12° \leq \theta \leq 62°$ and azimuthal angles $24° \leq \phi \leq 156°$. Impact parameters were selected by the multiplicity of charged particles, measured with LASSA and the 188 plastic scintillator - CsI(Tl) phoswich detectors of the Miniball/Miniwall array [19]; the combined apparatus covered 80% of the total solid angle.

Quasi-central collisions, corresponding to a reduced impact parameter of $b/b_{max} \le 0.3$, were selected by a gate on the charged-particle multiplicity distribution.

The data points on Fig. 1 show the d-α correlation functions, *1+R(q)*, defined in terms of the two-particle differential multiplicity, $dM_{d\alpha}(\vec{p}_d, \vec{p}_\alpha)/dp_d^3 dp_\alpha^3$, and the single particle differential multiplicities, $dM_d(\vec{p}_d)/dp_d^3$ and $dM_\alpha(\vec{p}_\alpha)/dp_\alpha^3$:

$$\Sigma\, dM_{d\alpha}(\vec{p}_d, \vec{p}_\alpha)/dp_d^3 dp_\alpha^3 = C \cdot [1 + R(q)] \Sigma\, dM_d(\vec{p}_d)/dp_d^3 \cdot \Sigma dM_\alpha(\vec{p}_\alpha)/dp_\alpha^3 \qquad (1)$$

Here, $\vec{p}_d$ and $\vec{p}_\alpha$ are the laboratory momenta of the two coincident particles, $q=\mu \cdot v_{rel}$ is the momentum of relative motion, and C is a normalization constant chosen such that $<R(q)>=0$ for large q-values where final-state interaction effects are negligible. The sums on each side of Eq. (1) extend over all particle energies and angles contributing to each bin of q. The product of the single particle yields, on the r.h.s. of Eq. (1) has been constructed by mixing particles from different events [20]. We apply the same centrality selection to both single and two particle multiplicity distributions in Eq. 1.

The d-α correlation function exhibits a large minimum at small relative momenta due to the mutual Coulomb repulsion and the structures at larger relative momenta that arise from nuclear interactions. The sharp peak in the d-α correlation function at q≈42 MeV/c corresponds to the first excited state of ^{6}Li at $E^*(^6Li)$ = 2.186 MeV ($J^\pi=3^+$, Γ=0.024 MeV, Γ_c/Γ=1.0) and the broad peak around 84 MeV/c stems mainly from the resonance at $E^*(^6Li)$ = 4.31 MeV ($J^\pi=2^+$, Γ=1.7 MeV, Γ_c/Γ=0.97) with small contributions from the resonance at $E^*(^6Li)$ = 5.65 MeV ($J^\pi=1^+$, Γ=1.5 MeV, Γ_c/Γ=0.74). Theoretically, the correlation function is commonly calculated using the angle-averaged Koonin-Pratt equation [1,5-8]:

$$R(q,P) = 4\pi \int dr \cdot r^2 \cdot K(q,r) \cdot S(r,q,P) \qquad (2)$$

The angle-averaged kernel *K(q,r)* is calculated from the radial part of the d-α elastic scattering relative wave function. The source function, *S(r,q,P)*, is defined as the probability for two-correlated particles with relative momentum *q* and total momentum *P* to be separated by a distance *r* when the last of the two particles is emitted. Most studies using Eq. (2) have assumed that the source function depends only on the relative distance, *r*, and not on relative momentum, *q* [1,2,5-8,21,22]. Under this assumption, source profiles with a Gaussian shape, $S(r) \propto \exp(-r^2/r_0^2)$, have been extensively used in the literature [2,21,22]. These sources, depending only on the geometry of the system, have failed in reproducing the line-shape of the correlation functions [21,22]. In particular, theoretical correlation functions that reproduce the magnitude of the E*=2.186 MeV peak, typically over-predict the E*~4.31 MeV peak [22].

Even if one accounts for long-lived secondary decays of unstable fragments, the situation does not improve because the relative magnitude of the two peaks does not change [7].

To study the effects of collective motion, we introduce a Monte Carlo simulation where deuterons and alpha particles are emitted from a spherical single-particle source with radius *R*. This source evaporates particles while undergoing collective expansion. Within the source, we randomly extract the positions, $\vec{r}_d$ and $\vec{r}_\alpha$, where deuteron and alpha particles are emitted. The velocities of the two emitted particles consist of a thermal and a collective component, $\vec{v}_d = \vec{v}_{d,th} + \vec{v}_{d,coll}(\vec{r}_d)$ and $\vec{v}_\alpha = \vec{v}_{\alpha,th} + \vec{v}_{\alpha,coll}(\vec{r}_\alpha)$. The thermal velocities, $\vec{v}_{d,th}$ and $\vec{v}_{\alpha,th}$, are randomly assigned according to Boltzmann distributions corresponding to an assigned temperature, T=4 MeV, consistent with measurements of isotopic and excited states thermometers [23]. The collective velocity components are parameterized as vector fields, $\vec{v}_{d,coll}(\vec{r}_d)$ and $\vec{v}_{\alpha,coll}(\vec{r}_\alpha)$, depending on the positions, $\vec{r}_d$ and $\vec{r}_\alpha$. Simulated particle trajectories are filtered through the acceptance of the LASSA array. Finally, the relative distance, $\vec{r} = \vec{r}_d - \vec{r}_\alpha$, and the momentum of relative motion, $\vec{q} = \mu(\vec{v}_d - \vec{v}_\alpha)$, are evaluated and used to construct the two-particle emitting source, *S(r,q)*, by integrating over total momentum, $P = |\vec{p}_d + \vec{p}_\alpha|$. The source function is then used in Eq. (2) to calculate the correlation function.

In Fig. 1 we compare our data to calculations performed with a pure-thermal emitting source (T=4 MeV and β_{flow}=0; dotted lines) with a radius R_0=10.5 fm. As for the p-p correlation function, the main effect of long-lived secondary decays is to reduce the magnitude of the correlation peaks without changing the shape. We take this into account by fitting the measured correlation function $R_{exp}(q)$ by $R_{\mathrm{exp}}(q) = \lambda \cdot R_{fast}(q)$, where λ represents the fraction of d-α pairs form the fast source. The main impact of varying R_0 is to change the widths of the peaks. The finite resolution of the LASSA array dominates the width of the first sharp peak at q=42 MeV/c, leaving no sensitivity to the source size. The width of the 84 MeV/c is found to scale almost linearly with source radius, i.e. Δq_{FWHM}(MeV/c)~25-1.2 R_0(fm). This sensitivity provides the opportunity to determine the source size, and potentially, the source density from d-α correlation functions. Calculations with a spherical source with R_0=10.5 fm approximately reproduce the width of the peak at q~84 MeV/c .

Choosing λ=0.8 normalizes the correlation function to the first peak at 42 MeV/c, but over-predict the height of the second peak at q~84 MeV/c and under-predicts the valley between the two peaks, as seen in the lower panel of Figure 1. These failures cannot be overcome by changing R_0, λ, the source temperature or by altering the source geometry.

Indeed, the d-α kernel function, K(r,q), has the same spatial extension close to the resonances at q~42 and 84 MeV/c: any change in the geometry of the source would change the height of the two peaks by the same factor and leave their ratio unmodified. In the following, we focus our attention upon this long standing and well documented [22] problem and defer optimizations with respect to source size, temperature and geometry to later investigations.

In order to resolve the observed discrepancies, we recognize that our selection of events with high multiplicities with $\hat{b} < 0.3$ includes events with non-negligible collective motion, both along and perpendicular to the beam axis [24]. For simplicity we parameterize these collective velocities as $\vec{v}_{d,coll}(\vec{r}_d) = c\beta_{flow}\vec{r}_d / R$ and $\vec{v}_{\alpha,coll}(\vec{r}_d) = c\beta_{flow}\vec{r}_\alpha / R$, where c is the velocity of light and β_{flow} represents the maximum collective velocity of a particle emitted at the surface of the system, i.e. when $\vec{r}_d = \vec{r}_\alpha = R$. This parameterization corresponds to a self-similar expansion [24-26].

Choosing pairs of protons and alpha particles from the simulation that are detected in LASSA, we constructed the source function *S(r)* that describes their relative separation at emission and found that collective motion induces an apparent reduction of the source size, consistent with studies at higher incident energies [16]. The thick solid line in Fig. 2 shows the profile of *S(r)* for a source with β_{flow}=0.2 , R=10.5 fm and T=4 MeV; the dotted line shows *S(r)* for a pure thermal source with β_{flow}=0, R=10.5 fm and T=4 MeV. The particle velocities are independent of position for the thermal source; thus particles emitted from any location in have an equal probability of being detected by the LASSA array and included in the correlation function. In this sense, the constructed correlation function probes the whole spatial extent of the emitting source. If collective motion is present, however, particles emitted from regions where the collective motion points away from LASSA will only be included in the correlation if the thermal velocity is larger than the local collective velocity. This limits the portion of the emitting source that can be probed by the experimental data and the source size appears reduced. In the particular case shown on Fig. 2, the apparent source size is reduced by as much as 50%.

The source size reduction is just one aspect of the influence of collective motion on correlations. Another is a dependence of the correlation function on the total momentum, $\vec{P} = \vec{p}_1 + \vec{p}_2$ of the particle pairs [1,2-8,16]. Such total momentum-dependence has also been interpreted at intermediate energies as a consequence of emission from cooling and expanding systems [2,21]. In Fig. 2 we show that the extracted source size for particles within a small relative momentum gate, q=0-50 MeV/c, is even smaller (thick dashed line) than the size of source corresponding to all extracted d-α pairs (solid line). Thus, collective motion makes the source function both *r*- and *q*-dependent. It happens because the d-α relative momentum, $\vec{q}$, has thermal and collective components, $\vec{q} = \vec{q}_{th} + \vec{q}_{coll}(\vec{r})$. The collective component, given by $\vec{q}_{coll}(\vec{r}) = \mu \frac{c\beta_{flow}}{R}\vec{r}$, depends on the relative distance, making the source both r- and q-dependent, i.e. *S=S(r,q)*, with small relative momentum values being positively correlated with correspondingly small relative distances. In the pure-thermal model, the relative momentum is independent of *r* and contains only a thermal component, $\vec{q} \approx \vec{q}_{th} = \mu(\vec{v}_{d,th} - \vec{v}_{\alpha,th})$. In Fig. 2 we show that the pure-thermal source profile obtained by gating at small relative momentum, *q*=0-50 MeV/c (thin dashed line) is exactly the same as the original ungated one (dotted line).

To show how collective motion influences the shape of the d-α correlation function, we separate it into two components, $R(q)=R_C(q)+R_N(q)$, where $R_C(q)$ and $R_N(q)$ correspond to the correlation functions generated by the mutual d-α Coulomb and nuclear interactions, respectively. The left and the right panels of Fig. 3 show, respectively, $1+R_C(q)$ and $1+R_N(q)$ obtained for a source with R=10.5 fm, T=4 MeV, and β_{flow} =0.0 (dotted line), β_{flow}=0.1 (solid line), β_{flow}=0.2 (dashed line) and β_{flow}=0.3 (dot-dashed line). In the comparison, the nuclear correlation functions (right panel) are all normalized to the integral of the first peak at q=42 MeV/c.

The Coulomb correlation function (left panel, Fig. 3) displays one prominent anti-correlation at small relative momentum due to the mutual Coulomb repulsion between the deuteron and the alpha particle. The width of the Coulomb dip increases with collective velocity, consistent with a decreasing apparent source size [27] caused by the collective motion in the system. In the right panel of Fig. 3 we show the calculated nuclear correlation functions (right panel, Fig. 3) in the region where the second peak is observed (q=50-110 MeV/c). The magnitude of the peak at 84 MeV/c decreases with increasing β_{flow}.

The relative momentum regions where resonant peaks exist, are mostly dominated by d-α pairs emitted at very small relative distances, $r \leq 2$ fm, corresponding to the average d-α spatial separation in the resonance. The two coincident particles have nearly the same collective velocities because they originate from nearly the same location. Thus, $\vec{q}_{coll}(r \approx 0) \approx 0$ and $\vec{q} \approx \vec{q}_{th}$, i.e. the relative momentum distribution can be described as a Boltzman distribution at the local temperature, *T*, of the source. The uncorrelated two-particle spectrum in the denominator of Eq. (1), on the other hand, is calculated by selecting d and α particles detected in different events. Either particle can originate from anywhere in the source, thus the collective velocities of d and α can be very different and $\vec{q}_{coll}(r) \neq 0$. The uncorrelated relative momentum spectrum is nearly exponential but has a larger slope, $T_{MIX}>T$, as compared to that of the coincidence two-particle spectrum. The correlation function, obtained by folding coincidence spectrum with the kernel K(r,q) and dividing by the uncorrelated spectrum, displays an exponential fall-off in those relative momentum regions where resonances are observed. The slope, T_{app}, of such fall-off is approximately given by the relation $1/T_{app}=1/T-1/T_{MIX}$. It is the origin of the attenuation of the height of the second peak observed in the right panel of Fig. 3. Thus the detailed shape of a d-α correlation function is sensitive not only to the volume but also to the collective motion and local temperature of the source. This sensitivity arises because the collective motion makes the effective temperature, T_{MIX}, of the denominator larger that the thermal temperature; this effect becomes increasingly important as the masses of the particles are increased, reflecting the increased importance of collective motion for heavier particles.

To compare our data in Fig. 1, we make more realistic assumptions about the geometry and the collective motion of the emitting source. Transverse collective expansions of about 2 MeV per nucleon have been previously observed in central Xe+Au collisions at E/A=50 MeV by studying complex fragment kinetic energy spectra [28]. For central events selected by high charged particle multiplicity, the longitudinal collective motion is larger [29]. Thus, we simulate the emission of deuterons and alpha particles to occur from a ellipsoidal source characterized by radii $R_Z=2R_X=2R_Y$, where z indicates the beam direction. Deuterons and α particle collective velocities are described as $\vec{v}_{d,coll}(\vec{r}_d) = c\beta_{flow}(\vec{r}_d/R_Z)$ and $\vec{v}_{\alpha,coll}(\vec{r}_d) = c\beta_{flow}(\vec{r}_\alpha/R_Z)$, respectively. This parameterization simulates the expected radial collective motion in the center of mass of the reaction and provides collective velocity components to those particles emitted close to the edges (r_d,r_α~R_Z) of the ellipsoid, representing the effects of incomplete stopping of the incident momenta.

Correlations functions have been calculated for a ranges of radii, (R_Z,R_X,R_Y), and for different values of the radial velocity parameter, β_{flow}=0.1, 0.2 and 0.3. We searched for those combinations of (R_Z,R_X,R_Y) and β_{flow} that provide a width of the peak at 84 MeV/c in reasonable agreement with the data. A reasonable description of that width is obtained for R_Z=15-20 fm, R_X=7.5-10 fm, R_Y=7.5-10 fm and $\beta_{\max}$~0.1. In the bottom panel of Fig. 1, we only show the results corresponding to R_Z=16 fm, R_X=R_Y=8 fm. Different curves correspond to

β_{flow}=0.1 (solid line), β_{flow}=0.2 (dashed line) and β_{flow}=0.3 (dot-dashed line). All simulated correlation functions shown in Fig. 1 are normalized to reproduce the magnitude of the first peak at q=42 MeV/c. The β_{flow}=0.1 value produces maximum expansion velocities in the central region that are consistent with previous measurements of transverse flow for Xe+Au collisions [28]. By introducing collective motion (solid line), we find that one can reduce significantly the observed discrepancies between experimental data and the pure-thermal source calculation (dotted line). The height of the peak at 84 MeV/c still remains slightly over-predicted. The valley between the peak at 42 and 84 MeV/c is well described by the calculations. More refined descriptions of collective motion (expansion, rotation, etc.) and better descriptions of the break-up geometry might provide somewhat better agreement. However, our main goal is to demonstrate that the interplay between thermal and collective motion introduces a q-dependence in the source function that can account for the long-standing difficulties in describing the line-shape of d-α correlation functions. Given the range of radii that yield reasonable descriptions of the data and assuming that the source contains about 80% of the total mass [28,29], we find that the source volume is consistent with average densities of the emitting source ranging between $\rho \sim 0.2\rho_0$ and $0.4\rho_0$ (with ρ_0=0.16 fm^{-3}, saturation density). Such density range is consistent with the freeze-out density values commonly employed in statistical models of multifragmentation [30].

The present work is limited to the study of inclusive d-α pairs, without any condition imposed on their velocities or total momentum. Such inclusive data contain contributions from different stages of the reaction. The existence of these multiple sources of deuteron and α particles has been predicted for example by the Expanding Emitting Source model [31] and is expected to influence the shape of correlation functions [7]. We expect that a quantitative comparison to experimental data can be improved by implementing our simplified single-source model within a more realistic scenario where multiple sources with different timescales are included. Such ideas can be also tested by gating on the total momentum of the correlated particles.

In summary, in this work we show that the interplay between source geometry and collective motion plays a key role in determining the line-shape of correlation functions constructed with complex particles. In addition to the previously studied effects induced by collective motion, we observe also the presence of a significant relative momentum dependence in the emitting source. We apply our ideas to study d-α correlation function measured in Xe+Au collisions at E/A=50 MeV. Realistic assumptions about the volume, the temperature and the collective motion in the system allow us to obtain a semi-quantitative description of the data and explain the difficulties encountered in previous studies.

This work is supported by the National Science Foundation under Grant Nos. PHY-0245009 and PHY-0555893. Part of this work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Figures

FIGURE 1. d-α correlation function. Top panel: overall view of the correlation function. Bottom panel: view emphasizing the second resonance at ~84 MeV/c. Circles: d-α correlation function measured in Xe+Au collisions at E/A=50 MeV. Lines: calculated correlation functions for a pure-thermal spherical source with R=10.5 fm, T=4 MeV (dotted line), and an ellipsoidal source with R_Z=16fm,R_X=8fm,R_Y=8fm, T=4 MeV and collective motion parameter β_{flow}=0.1 (solid line), 0.2 (dashed line) and 0.3 (dot-dashed line).

FIGURE 2. Calculated d-α sources for a spherical single-particle source with R=10.5 fm and T=4 MeV. Pure-thermal source calculations, β_{flow}=0.0, are represented by a dotted line (all *q*'s) and by a thin dashed line (q=0-50 MeV/c). The thick solid and thick dashed lines represent the spherical source with β_{flow}=0.2 and, respectively, without and with a q=0-50 MeV/c gate applied.

FIGURE 3. Effects of collective motion on Coulomb (left panel) and Nuclear (right panel) correlation functions. Dotted, solid, dashed and dot-dashed lines represent, respectively, β_{flow}=0.0, β_{flow}=0.1, β_{flow}=0.2 and β_{flow}=0.3.

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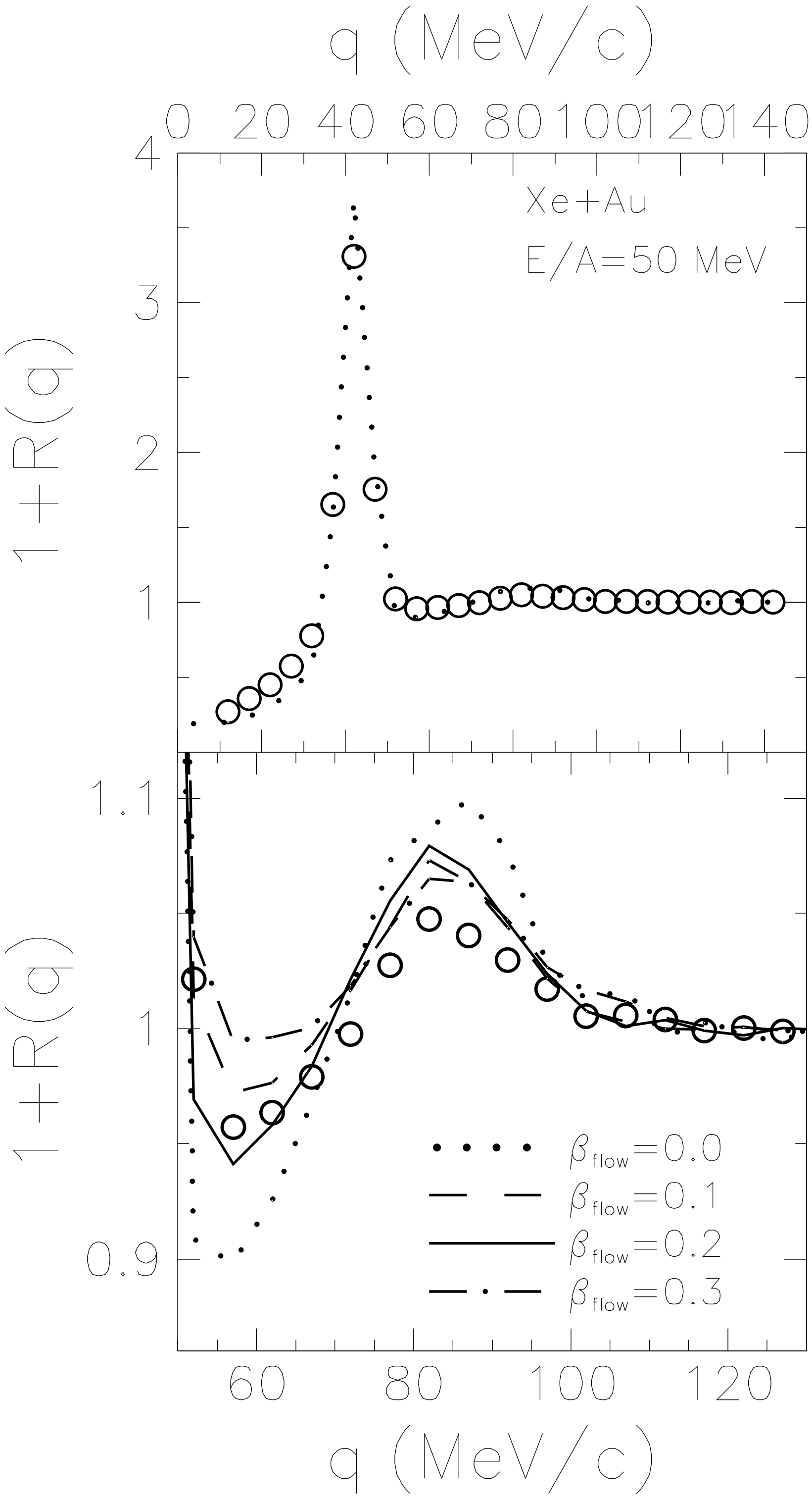
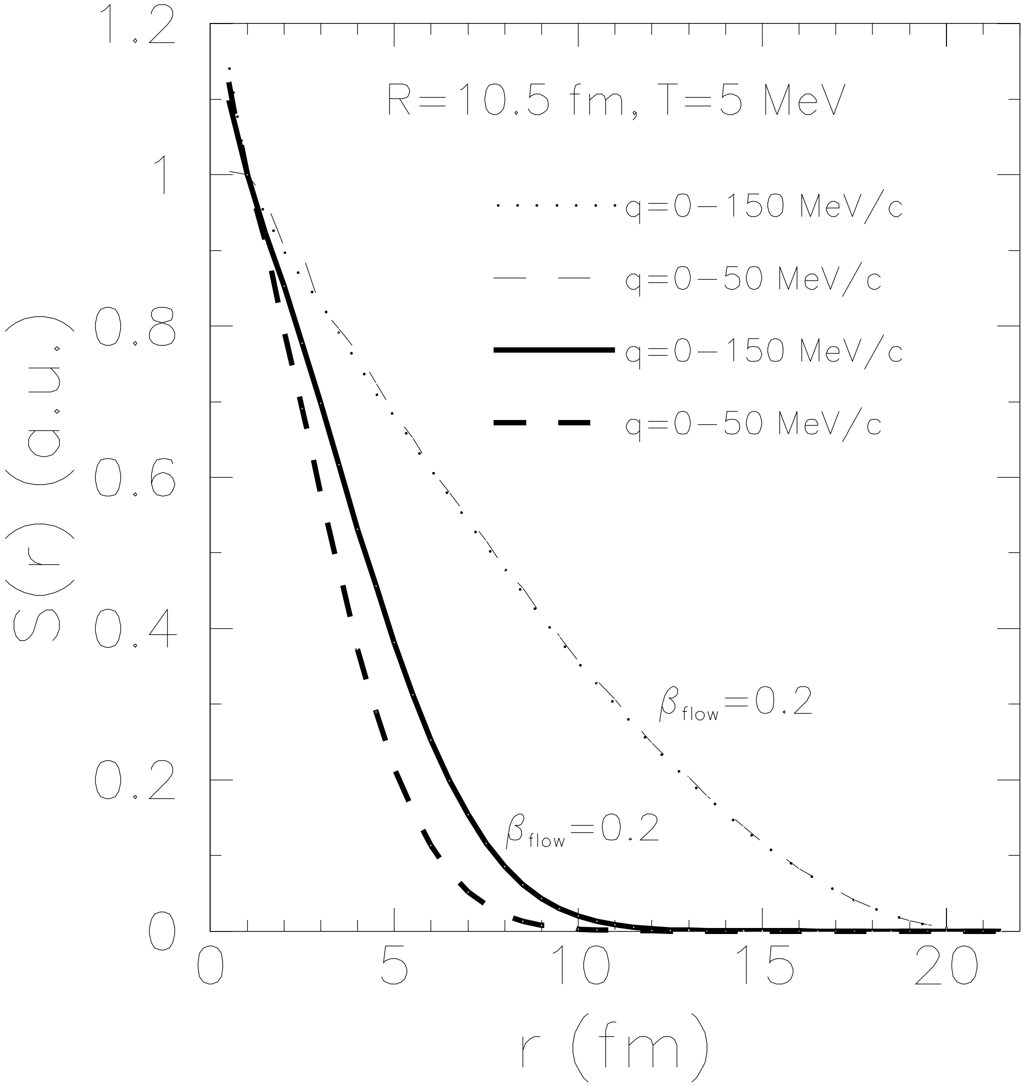
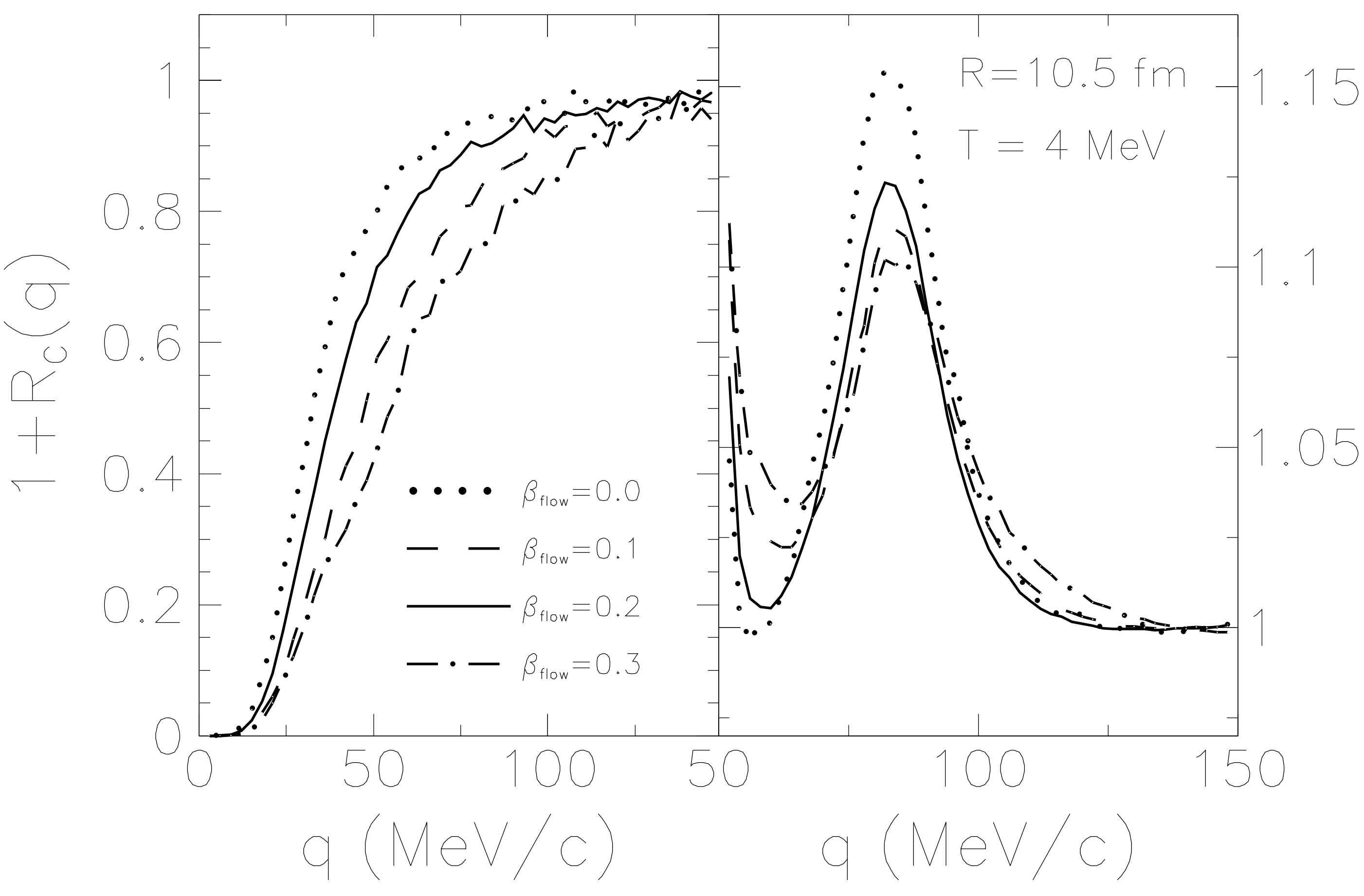


q (MeV/c)
0 20 40 60 80 100 120 140
4
3
2
1
1+R(q)
Xe+Au
E/A=50 MeV
1.1
1
0.9
1+R(q)
β_{flow}=0.0
β_{flow}=0.1
β_{flow}=0.2
β_{flow}=0.3
60 80 100 120
q (MeV/c)


R=10.5 fm, T=5 MeV
q=0−150 MeV/c
q=0−50 MeV/c
q=0−150 MeV/c
q=0−50 MeV/c
β_{flow}=0.2
β_{flow}=0.2
S(r) (a.u.)
r (fm)
0
0.2
0.4
0.6
0.8
1
1.2
0
5
10
15
20



1+R_c(q)
1+R_N(q)
q (MeV/c)
q (MeV/c)
R=10.5 fm
T = 4 MeV
β_flow=0.0
β_flow=0.1
β_flow=0.2
β_flow=0.3