Throwing triangles against a wall: ground state of ^{12}C from highest-energy collisions

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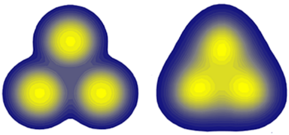


Physics Symposium, 24th CBM Week
10 September 2014, Cracow

[research with Enrique Ruiz Arriola, Piotr Bożek, Maciej Rybczyński]

Instead of outline

Two phenomena are related:

α clustering in light nuclei

$\updownarrow$

harmonic flow in ultra-relativistic nuclear collisions

Surprising link:

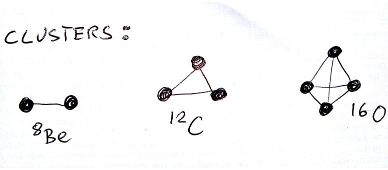
lowest-energy ground-state structure $\longleftrightarrow$ highest energy reactions

- New method of investigating many-particle nuclear correlations
- Another test of collective dynamics/harmonic flow

α clusters

Some history

David Brink: *After Gamow's theory of α-decay it was natural to investigate a model in which nuclei are composed of α-particles. Gamow developed a rather detailed theory of properties in his book "Constitution of Nuclei" published in 1931 before the discovery of the neutron in 1932. He supposed that 4n-nuclei like ^{8}Be, ^{12}C, ^{16}O ... were composed of α-particles*



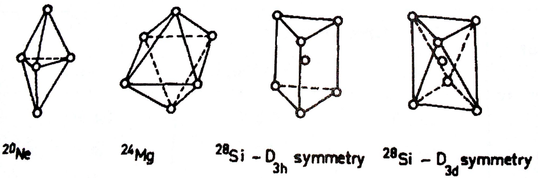
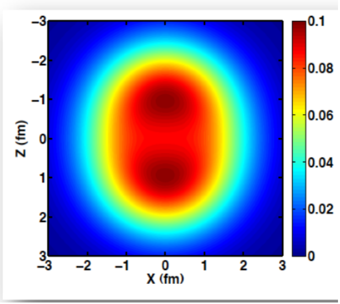
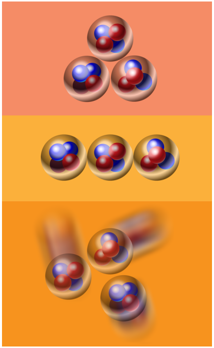


Fig. 1. Alpha-particle configuration for some $4N$ nuclei.

α clusters in light nuclei



^{9}Be



^{12}C

ground

Hoyle 0^{+}

other excited, 2^{+} ...

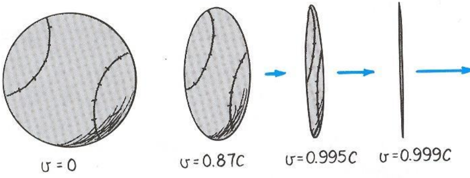
How can we detect the α clusters in the ground state?
What is their spatial arrangement?
Assessment of n-body correlations (one-body not enough)

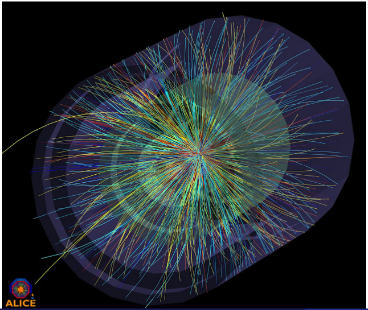
[Recent status: SOTANCP3 Conference, Yokohama, May 2014]

Flow

Ultra-relativistic A+A collisions (LHC, RHIC, SPS)

- Lorentz contraction
- Collision: essentially instantaneous passage, frozen configuration
- Reduction of the ground-state wave function of the nucleus **(like measurement)**

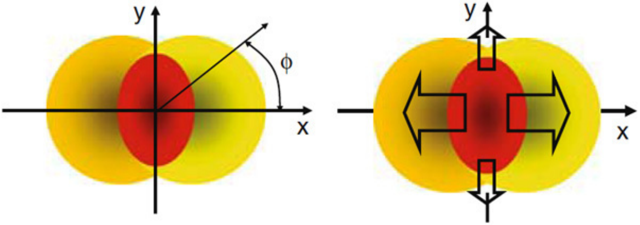




- detection of particles in the transverse direction (mid-rapidity)

Phenomenon of flow

Quark-gluon plasma is formed!



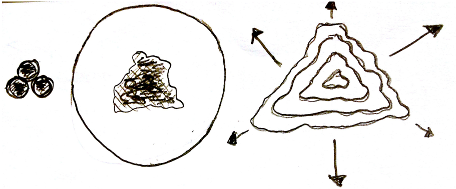
"Initial shape – final flow" transmutation detectable in the asymmetry of the momentum distribution of detected particles – follows from collectivity

Merge the two ideas (α's and flow) $\rightarrow$

[WB & ERA, PRL 112 (2014) 112501]

From α clusters to flow in relativistic collisions

α clusters $\rightarrow$ asymmetry of shape $\rightarrow$ asymmetry of initial fireball $\rightarrow$
$\rightarrow$ hydro or transport $\rightarrow$ collective harmonic flow



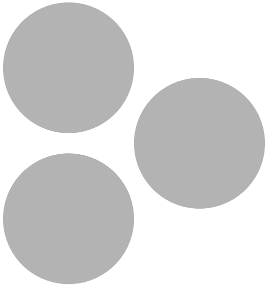
nuclear triangular geometry $\rightarrow$ fireball triangular geometry $\rightarrow$ triangular flow

What are the signatures, chances of detection?
(some blurring by fluctuations)
"Easy snap-shot but difficult development"

Described later: ^{3}He–Au at RHIC [Sickles et al. (PHENIX) 2013]
The case of ^{12}C is more promising, as it leads to more abundant fireballs

Our modeling ^{12}C

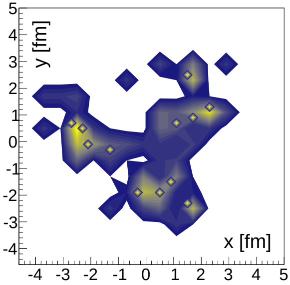
Three α's in a triangular arrangement, generate nucleon positions with Monte Carlo, parameters (size of the cluster, distance between clusters) properly adjusted (fit one-body radial distributions from other calculations, fit EM form factor)



^{12}C-^{208}Pb – single event

Why ultra-relativistic?

Reaction time is much shorter than time scales of the structure
$\rightarrow$ a frozen "snapshot" of the nuclear configuration



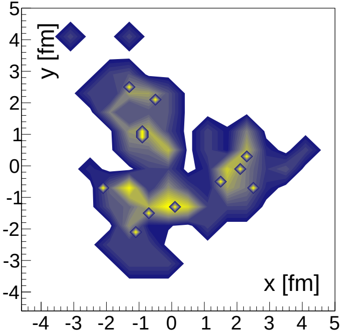
wounding range determined by $\sigma_{\mathrm{NN}}^{\mathrm{inel}}$

($N_w > 70$ - flat-on orientation)

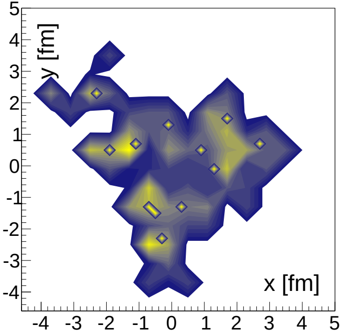
Imprints of the three α clusters clearly visible

Simulations with GLISSANDO 2

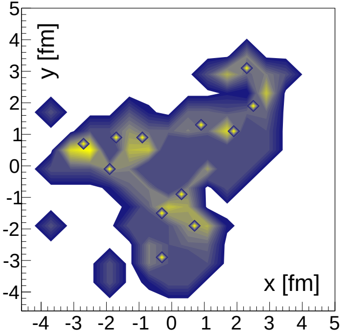
... more events



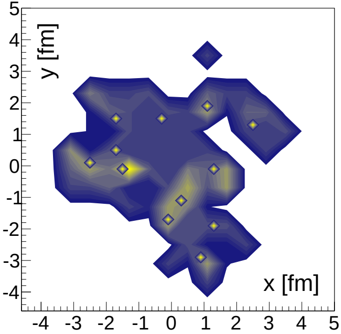
... more events



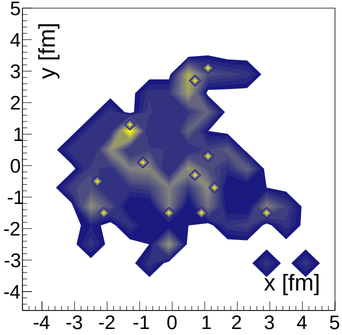
... more events



... more events



... more events



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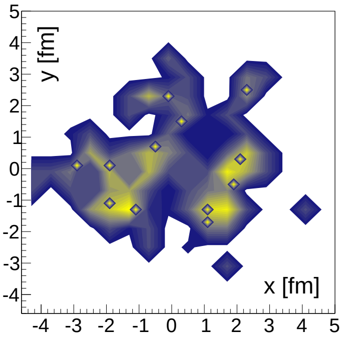

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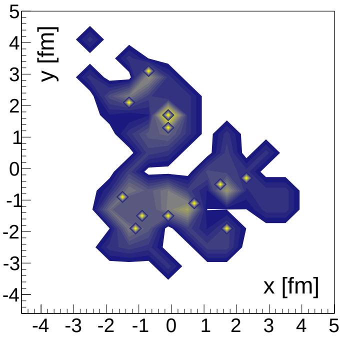

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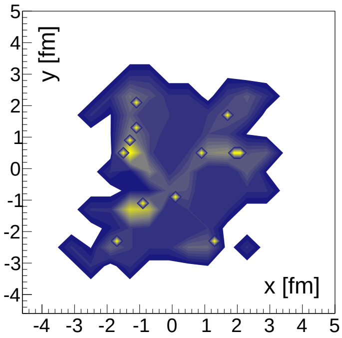
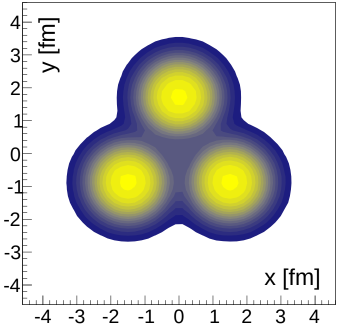


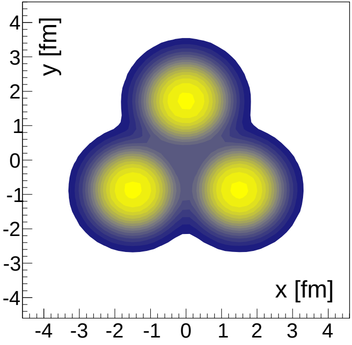
^{12}C

Our intrinsic distributions in ^{12}C: three α's in a triangular arrangement

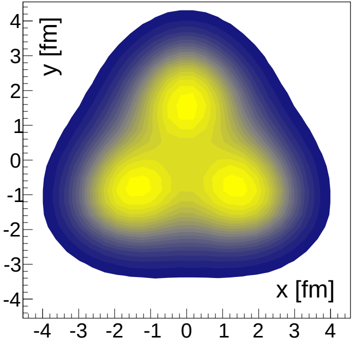


Geometry of nucleus → geometry of fireball

Triangular nucleus causes triangular "damage"!



intrinsic density of ^{12}C →



geometry of the fireball (flat-on collision)

Eccentricity parameters

We need some quantitative measures of deformation (heavily used in heavy-ion analyses)

Eccentricity parameters ϵ_n (Fourier analysis)

$$\epsilon_n e^{in\Phi_n} = \frac{\sum_j \rho_j^n e^{in\phi_j}}{\sum_j \rho_j^n}$$

describe the shape of each event (j labels the sources in the event, n=rank, Φ_n is the principal axis angle)
$n = 2$ – ellipticity, $n = 3$ – triangularity, ...

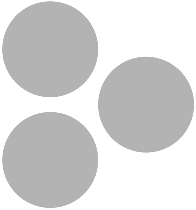
Two components:

- intrinsic (from existent mean deformation of the fireball)
- from fluctuations

Geometry vs multiplicity correlations in ^{12}C-Pb

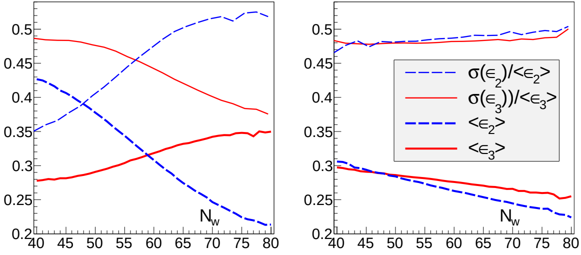
Two cases of angular orientation

cluster plane parallel or perpendicular to the transverse plane:



higher multiplicity	lower multiplicity
higher triangularity	lower triangularity
lower ellipticity	higher ellipticity

Ellipticity and triangularity vs multiplicity



clustered unclustered

Clusters: (qualitative signal!)

When $N_w \nearrow$ then $\langle\epsilon_3\rangle \nearrow$ and $\langle\epsilon_2\rangle \searrow$

and $\langle\sigma(\epsilon_3)/\epsilon_3\rangle \searrow$, $\langle\sigma(\epsilon_2)/\epsilon_2\rangle \nearrow$

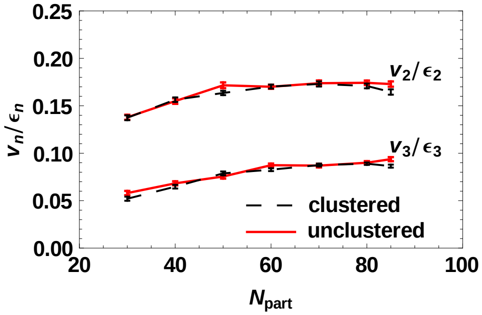
No clusters:

similar behavior for $n = 2$ and $n = 3$

Shape-flow transmutation

The eccentricity parameters are transformed (in all models based on collective dynamics) into asymmetry of the transverse-momentum flow.
Linear response:

v_n grows with ϵ_n



[Bożek 3+1 viscous hydro + THERMINATOR]

Hydro without hydro

We have to a very good approximation

$$v_n = \kappa_n \epsilon_n, \quad n = 2, 3, \ldots$$

(κ_n depends on mutiplicity and hydro details)

Cumulant moments:

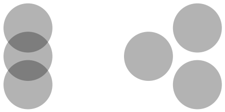
$$\epsilon_n\{2\}^2 = \langle \epsilon_n^2 \rangle, \; \epsilon_n\{4\}^4 = 2\langle \epsilon_n^2 \rangle - \langle \epsilon_n^4 \rangle$$

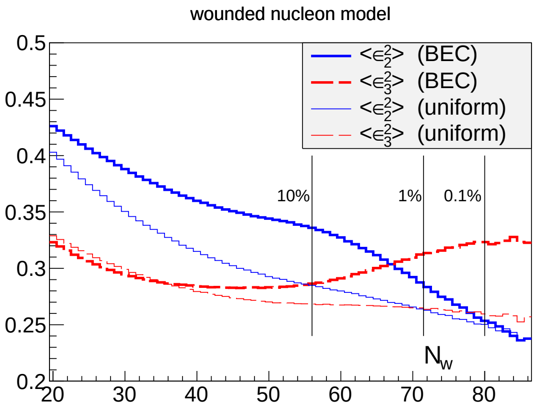
Ratio's insensitive to response:

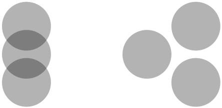
$$\frac{v_n\{m\}}{v_n\{2\}} = \frac{\epsilon_n\{m\}}{\epsilon_n\{2\}}, \quad m = 4, 6, \ldots$$

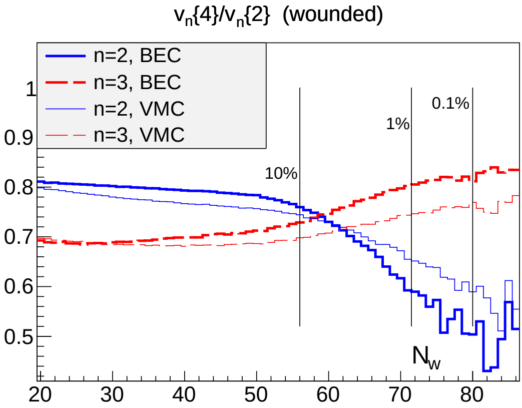
(infer info on flow from just the eccentricities, no hydro!)

Cumulant moments

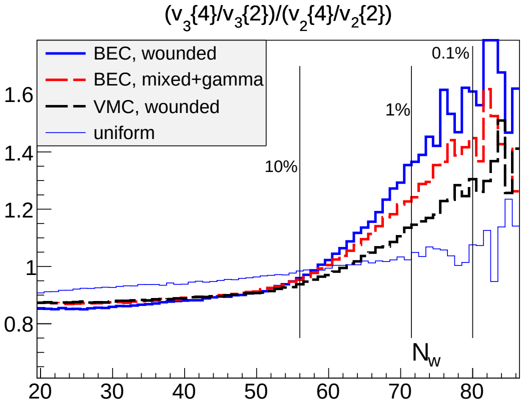


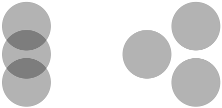





vn{4}/vn{2} (wounded)
n=2, BEC
n=3, BEC
n=2, VMC
n=3, VMC
10%
1%
0.1%
Nw
0.5
0.6
0.7
0.8
0.9
1
20
30
40
50
60
70
80

Double ratio of cumulant moments





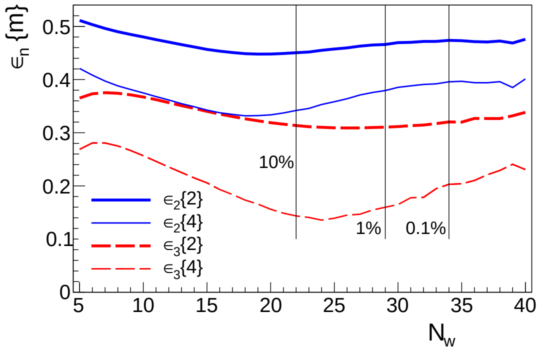
^{3}He-Au

^{3}He-Au

(being presently analyzed by PHENIX)

[hydro: J. Nagle et al., arXiv:1312.4565]

[hydro without hydro: Piotr Bożek and WB, arXiv:1409.2160]



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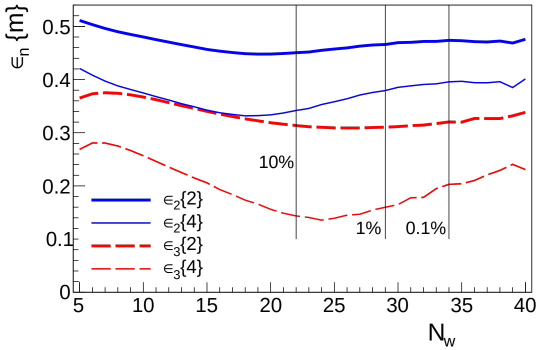
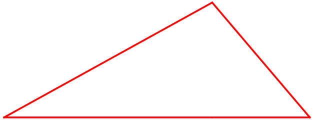
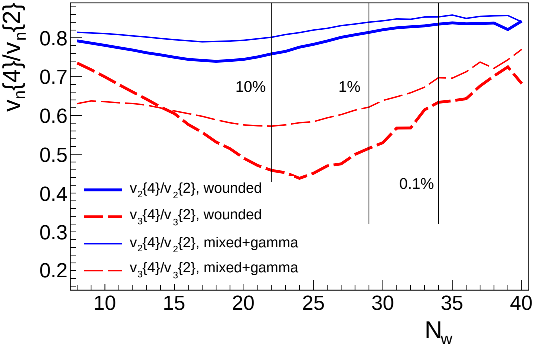




(not equilateral)

Ratio for ^{3}He-Au



(to be confirmed by the experiment!)

Conclusions

Nuclear structure from ultra-relativistic heavy ion collisions

Snapshots of the ground-state wave function

Spatial correlations in the ground state → harmonic flow

Signatures in clustered ^{12}C-^{208}Pb collisions

- Increase of triangularity with multiplicity for the highest multiplicity events
- Anticorrelation of ellipticity and triangularity
- Very clear signals from ratios of cumulant moments
- Stronger effect at lower $\sigma_{NN}^{\rm inel}$ (i.e., at lower collision energies)
- Even stronger effect on the ^{12}C side in rapidity
- Ratios depend on the nuclear wave function and the initial-state model, but not on hydro

Possible data (NA61@SPS, RHIC) would allow to place constrains on the spatial structure of the light projectile. Conversely, the knowledge of the nuclear distributions helps to verify the fireball formation models

Back-up

Intrinsic distributions

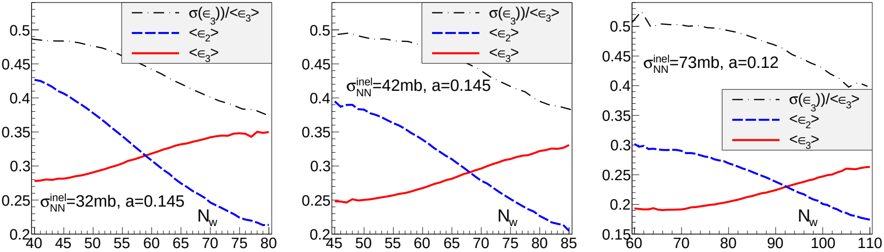
Ground state of ^{12}C is a 0^+ state (rotationally symmetric wave function).
The meaning of *deformation* concerns multiparticle correlations between the nucleons

Superposition over orientations:

$$|\Psi_{0^+}(x_1,\ldots,x_N)\rangle = \frac{1}{4\pi}\int d\Omega \Psi_{\rm intr}(x_1,\ldots,x_N;\Omega)$$

The *intrinsic* density of sources of rank n is defined as the average over events, where the distributions in each event have aligned principal axes: $f_n^{\rm intr}(\vec{x}) = \langle f(R(-\Phi_n)\vec{x})\rangle$. Brackets indicate averaging over events and $R(-\Phi_n)$ is the inverse rotation by the principal-axis angle in each event

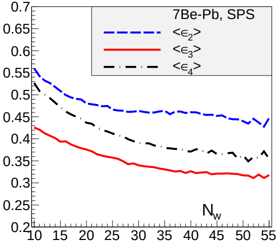
Dependence on the collision energy

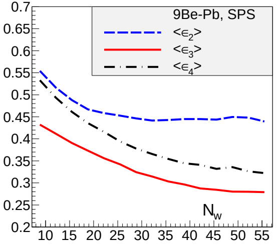


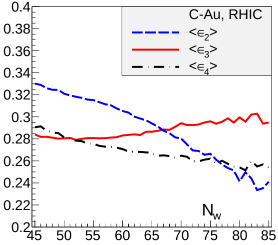
$\sigma_{\rm NN}^{\rm inel}$ =32mb (SPS) 42mb (RHIC) 72mb (LHC)

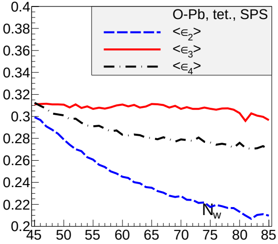
Qualitative conclusions hold from SPS to the LHC

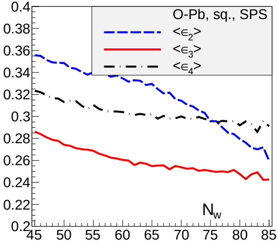
Other systems
(distributions matched to Wiringa's et al. radial densities)











[work with Maciej Rybczyński]