Alpha clustering from relativistic collisions

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[details in WB& E. Ruiz Arriola, **arXiv:1312.0289**]

Instead of outline

(WPCF 2013 $\to \alpha$)

Two phenomena are related:

α clustering in light nuclei

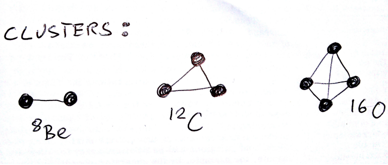
$\updownarrow$

harmonic flow in ultra-relativistic A+B collisions

low-energy structure $\longleftrightarrow$ highest energy mini bangs (!)

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*



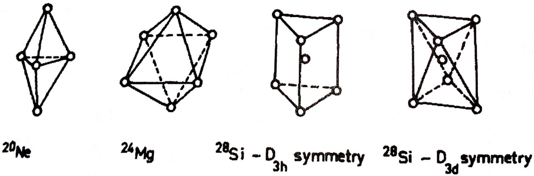


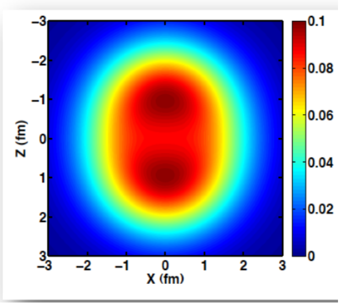
Fig. 1. Alpha-particle configuration for some 4*N* nuclei.

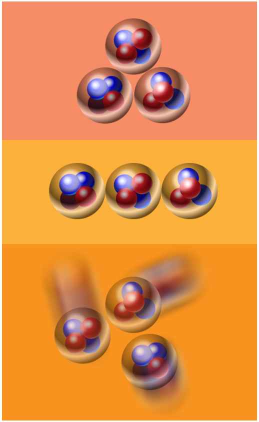
Shell model and its problems

Michael P. Carpenter: *However, in the 1960s, excited states in nuclei that comprise equal numbers of protons and neutrons, (e.g., ^{12}C and ^{16}O) were identified that could not be described by the shell model, and it was suggested by Ikeda and others that these states could be associated with configurations composed of α particles*

α decay of ^{212}Po

Present status





ground

Hoyle 2^+

other excited

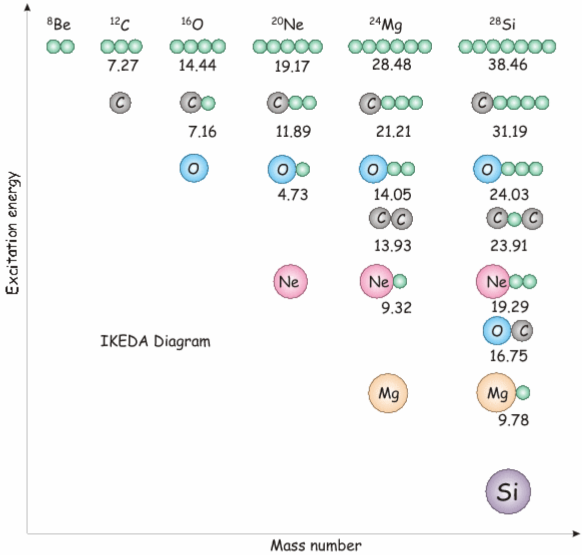
^{9}Be

^{12}C

[Martin Freer at WPCF2013, H. Fynbo+Freer: Physics 4 (2011) 94]

ab initio calculations up to $^{16}O \longleftrightarrow$ strong α clusterization

Ikeda diagram



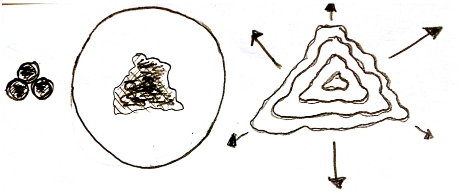
α condensation

Funaki et al.: *certain states in self-conjugated nuclei ... can be described as product states of α particles, all in the lowest $0S$ state. We define a state of condensed α particles in nuclei as a bosonic product state in good approximation, in which all bosons occupy the lowest quantum state of the corresponding bosonic mean-field potential*

Another approach: Fermionic Molecular Dynamics

From α clusters to flow in relativistic collisions

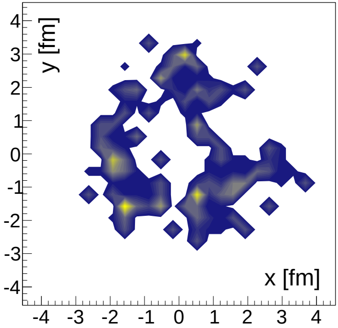
α clusters $\to$ asymmetry of shape $\to$ asymmetry of initial fireball $\to$
$\to$ hydro or transport $\to$ collective harmonic flow



What are the chances of detection?

Related idea: triton/^{3}He–Au at RHIC in 2015 [Sickles (PHENIX) 2013]
The case of light nuclei is more promising, as it leads to abundant fireballs

^{12}C-^{208}Pb – single event



Imprints of the α clusters clearly visible

The meaning of *intrinsic*

Ground-state nuclei are (mostly) in 0^+ states (rotationally symmetric)
The meaning of deformation concerns multiparticle correlations between nucleons.

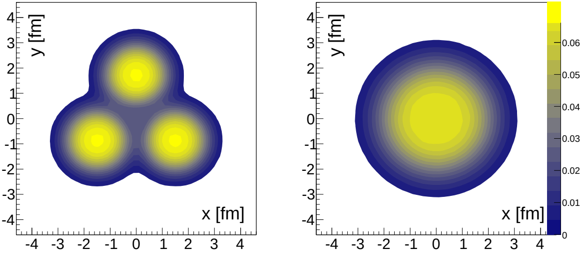
$$|\Psi_{0^+}(x_1,\ldots,x_N)\rangle = \frac{1}{4\pi}\int d\Omega \Psi_{\rm intr}(x_1,\ldots,x_N;\Omega)$$

(holds from deuterium to U)

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

^{12}C-^{208}Pb – intrinsic average over events

Intrinsic distributions: 3 α's in a triangular arrangement



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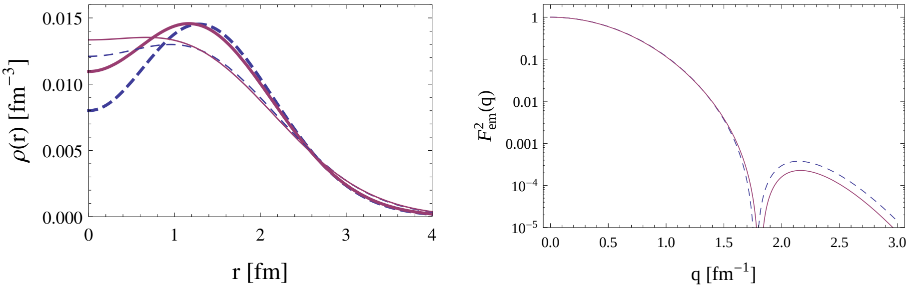
Constraints from EM form factor

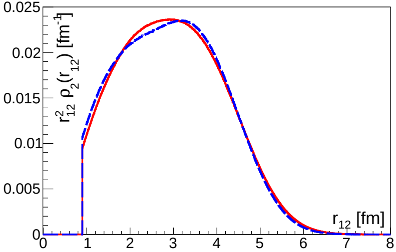


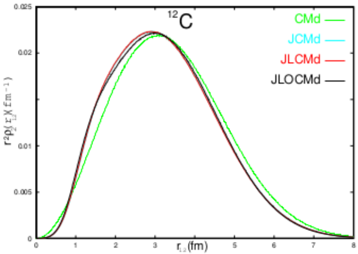
Electric charge density (thin lines) and the corresponding distribution of the centers of nucleons (thick lines) in ^{12}C for the data and BEC calculations (dashed lines), and for the FMD calculations (solid lines), plotted against the radius.

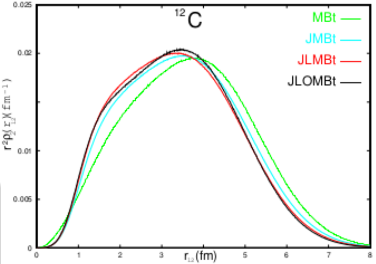
Central depletion

Distribution of pairs

Radial density in the relative NN distance r_{12}







[Buendia et al. 2004]

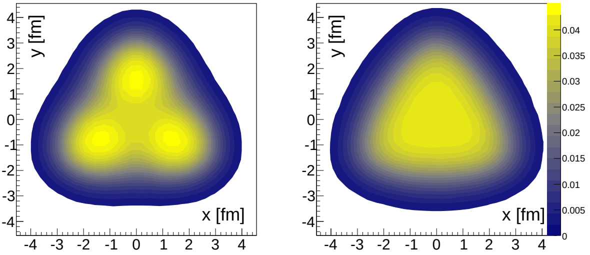
Our Monte Carlo

The α cluster structure is modeled sufficiently accurately

^{12}C–^{208}Pb collision

Mixed Glauber model at SPS conditions: $n \sim \frac{1-a}{2} N_{\rm w} + a N_{\rm bin}, \quad a = 0.12$

Intrinsic distributions in the *cluster plane* in the fireball, $N_w > 70$ – large multiplicity



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Eccentricity parameters

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

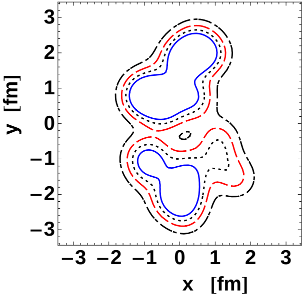
describe the shape (j labels the sources in the event, n=rank)

Two components:

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

Digression: d-Pb

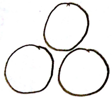
Initial entropy density in a d-Pb collision with $N_{\text{part}} = 24$ [Bozek 2012]



Fluctuations around the intrinsic ellipticity

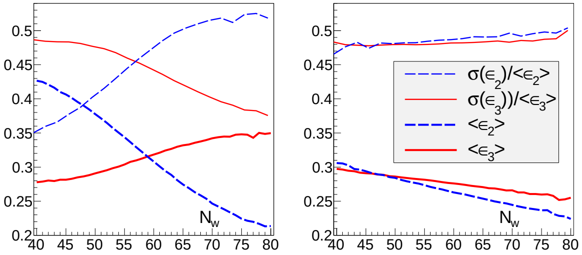
Geometry vs multiplicity in ^{12}C-Pb

The cluster plane parallel or perpendicular to the transverse plane:



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

Ellipticity and triangularity vs multiplicity



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Clusters:

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

and $\langle\sigma(\epsilon_3)/\epsilon_3\rangle \searrow$, $\langle\sigma(\epsilon_2)/\epsilon_2\rangle \nearrow$ tending to $\sqrt{4/\pi - 1} \sim 0.52$

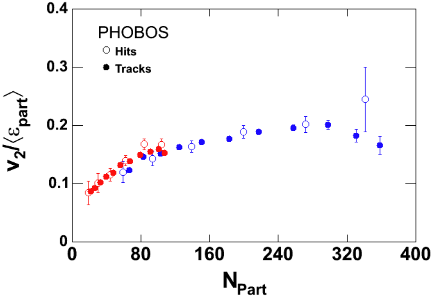
No clusters:

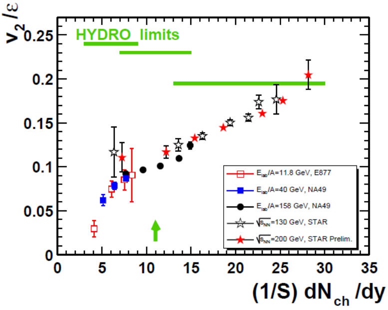
similar behavior for $n = 2$ and $n = 3$

Shape-flow transmutation

The eccentricity parameters are transformed (in all models based on collective dynamics) into asymmetry of the transverse-momentum flow. It has been found that

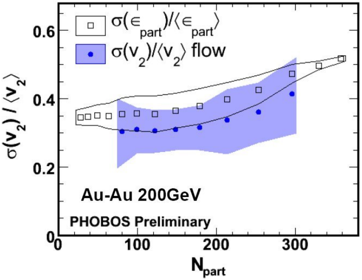
$$\langle v_n \rangle \simeq A \langle \epsilon_n \rangle$$





E-by-e fluctuations

$$\frac{\sigma(v_n)}{\langle v_n \rangle} \simeq \frac{\sigma(\epsilon_n)}{\langle \epsilon_n \rangle}$$



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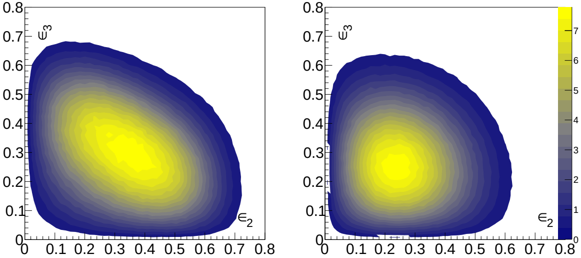
Measured flow coefficients reflect the initial shape eccentricities

Triangularity vs ellipticity



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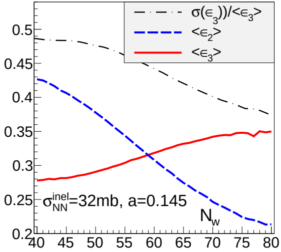
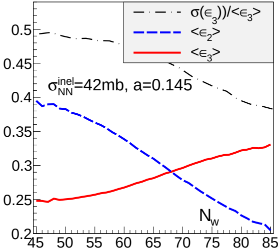
Clusters:

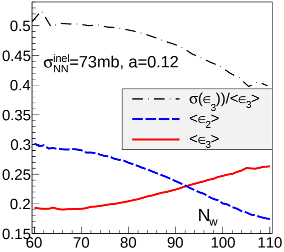
Anticorrelation: $\rho(\epsilon_2, \epsilon_3) \simeq -0.3$



32mb (SPS)



42mb (RHIC)



72mb (LHC)

Qualitative conclusions hold from SPS to the LHC

Why small on big?

small nucleus $\rightarrow$ large deformation from clusters
big nucleus $\rightarrow$ large fireball, collectivity

small on small $\rightarrow$ more difficult evolution, other signatures (requires careful studying)

big on big (U+U, Cu+Au) $\rightarrow$ signatures of nuclear deformation (but not clustering) [Filip, Volshin 2010, Rybczyński, WB, Stefanek 2011]

ultrarelativistic (RHIC, LHC) at central rapidities $\rightarrow$ tested evolution codes exist

Conclusions

Signatures of clustered ^{12}C-^{208}Pb collisions $\rightarrow$

- Increase of ϵ_3 and v_3 with multiplicity for the highest multiplicity events
- Decrease of scaled variance ϵ_3 and v_3 with multiplicity for the highest multiplicity events
- Anticorrelation of ϵ_2 and ϵ_3, or v_2 and v_3

Extensions:

- Other systems
- More detailed modeling

Possible future data (NA61?) in conjunction with a detailed knowledge of the dynamics of the evolution of the fireball would allow to place constrains on the α-cluster structure of the colliding nuclei.
Conversely, the knowledge of the clustered nuclear distributions may help to verify the fireball evolution models