Elliptic flow with polarized beams

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Outline

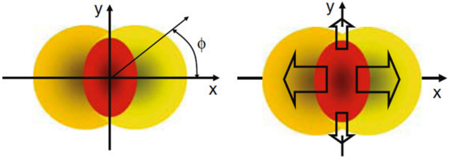
- Collectivity: shape-flow transmutation
- Small systems, d+A
- Polarized deuteron and other light nuclei with $j \geq 1$
- Clustered light nuclei

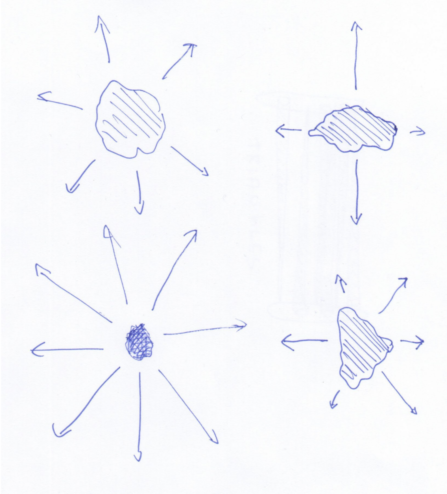
Shape-flow transmutation

Shape-flow transmutation

[Ollitrault '92]

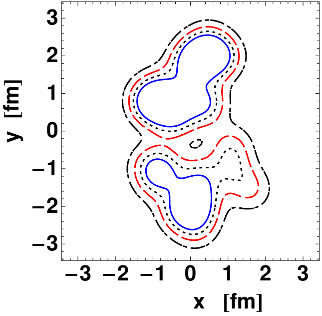
many particles, final/intermediate-state interactions, generation of flow

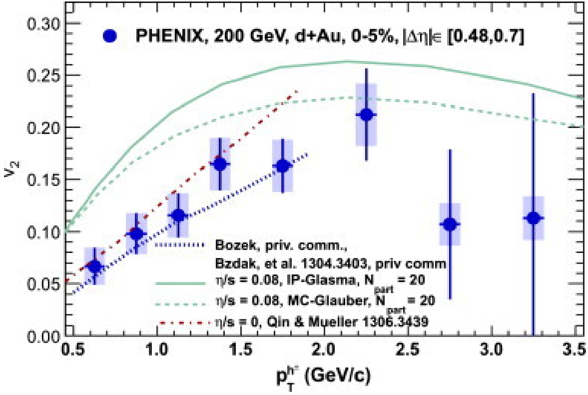




d+A

"small" systems [PB 2011]





Polarized deuteron

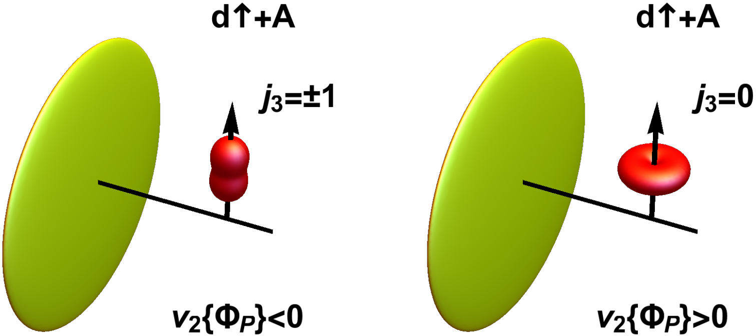
Motivation: collectivity vs CGC dispute

Deuteron

- $J^P = 1^+$, can be polarized – not SF!
- predominantly $^3S_1$-wave
- small ($\sim 5\%$) $^3D_1$-wave admixture

$^{2S+1}L_j$ notation

Cartoon



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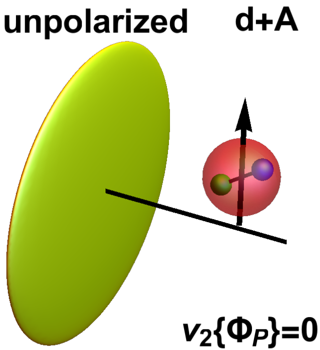

Wave function

$$|\Psi(r;j_3)\rangle = U(r)|j=1,j_3,L=0,S=1\rangle + V(r)|j=1,j_3,L=2,S=1\rangle$$

Explicitly, with the Clebsch-Gordan decomposition onto states $|LL_3\rangle|SS_3\rangle$,

$$|\Psi(r;1)\rangle = U(r)|00\rangle|11\rangle + V(r)\left[\sqrt{\tfrac{3}{5}}|22\rangle|1\,{-1}\rangle - \sqrt{\tfrac{3}{10}}|21\rangle|10\rangle + \sqrt{\tfrac{1}{10}}|20\rangle|11\rangle\right]$$
$$\ldots$$

Orthonormality of the spin parts yields

$$|\Psi(r,\theta,\phi;\pm1)|^2 = \tfrac{1}{16\pi}\left[4U(r)^2 - 2\sqrt{2}\left(1-3\cos^2\theta\right)U(r)V(r) + \left(5-3\cos^2\theta\right)V(r)^2\right]$$
$$|\Psi(r,\theta,\phi;0)|^2 = \tfrac{1}{8\pi}\left[2U(r)^2 + 2\sqrt{2}\left(1-3\cos^2\theta\right)U(r)V(r) + \left(1+3\cos^2\theta\right)V(r)^2\right]$$

. . . the $U(r)V(r)$ terms are not so small!

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Of course,

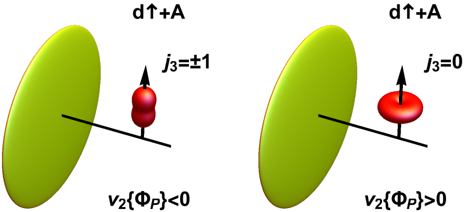
$$\sum_{j_3}|\Psi(r,\theta,\phi;j_3)|^2 = \frac{3}{4\pi}[U(r)^2 + V(r)^2]$$

Ellipticity of $|\Psi|^2$

Eccentricity of rank $n \geq 2$ with respect to a fixed axis at Φ_P for a distribution $f(\vec{\rho})$ is

$$\epsilon_n\{\Phi_P\} = -\frac{\int \rho d\rho d\alpha \cos\left[n(\alpha - \Phi_P)\right] f(\vec{\rho})\rho^n}{\int \rho d\rho d\alpha f(\vec{\rho})\rho^n},$$

$\vec{\rho}$ is in the transverse plane, α is the azimuth



$$\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} = \frac{\int d^3r\, r^2\{\frac{2\sqrt{2}}{5}U(r)V(r) - \frac{1}{5}V(r)^2\}}{\int d^3r\, r^2\{\frac{2}{3}U(r)^2 - \frac{2\sqrt{2}}{15}U(r)V(r) + \frac{11}{15}V(r)^2\}} \simeq 0.11$$

$$\epsilon_2^{|\Psi|^2_{j_3=\pm1}}\{\Phi_P\} \simeq -0.47\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} \simeq -0.05$$

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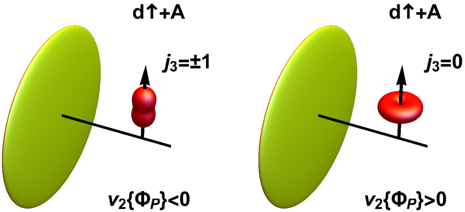
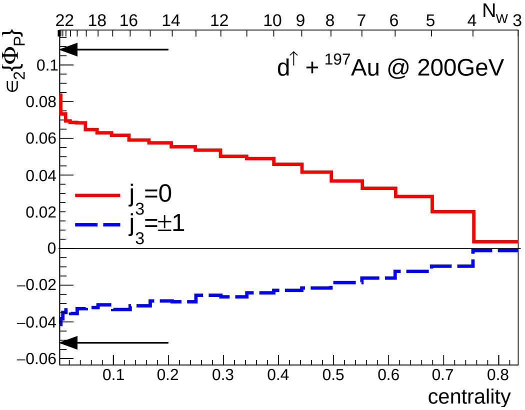


$$\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} = \frac{\int d^3r\, r^2\{\cancel{\frac{2\sqrt{2}}{5}U(r)V(r)} - \frac{1}{5}V(r)^2\}}{\int d^3r\, r^2\{\frac{2}{3}U(r)^2 - \cancel{\frac{2\sqrt{2}}{15}U(r)V(r)} + \frac{11}{15}V(r)^2\}} \simeq \cancel{0.11} - 0.007$$

$$\epsilon_2^{|\Psi|^2_{j_3=\pm1}}\{\Phi_P\} \simeq -0.47\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} \simeq \cancel{-0.05}\ 0.003$$

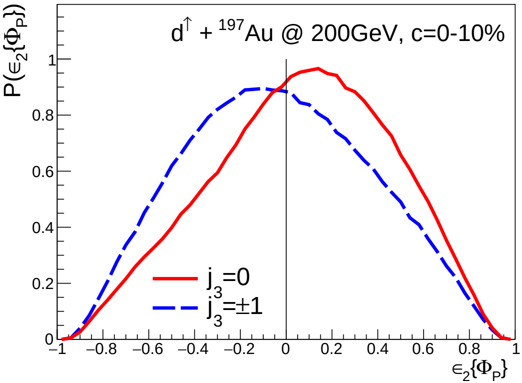
Ellipticity of the fireball relative to polarization axis

Wounded nucleon model + binary, $S \sim N_\mathrm{W}/2 + aN_\mathrm{bin}$, as implemented in `GLISSANDO`



$\sim$30% reduction compared to $\epsilon_2^{|\Psi|^2}$ (nucleons from Au)

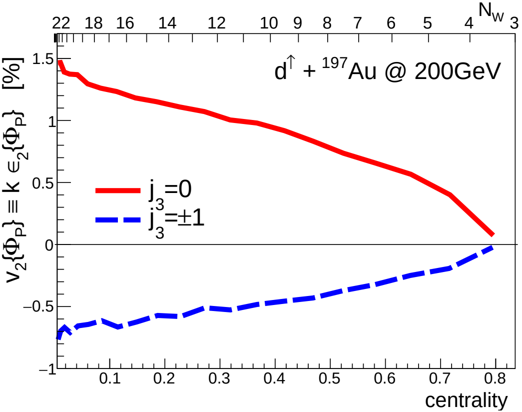
Distribution of ellipticity (most central)



v_2 relative to polarization axis

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos\left[2(\phi - \Phi_P)\right]$$

$$v_2 \simeq k\epsilon_2, \quad k \sim 0.2$$



$v_2\{\Phi_P\}$ with imperfect polarization

For $j = 1$ nuclei, the *tensor polarization* is

$$P_{zz} = n(1) + n(-1) - 2n(0)$$

$n(j_3)$ – fraction of states with angular momentum projection j_3
In our case

$$v_2\{\Phi_P\} \simeq k\, \epsilon_2^{j_3=\pm 1}\{\Phi_P\} P_{zz}$$

- max for $P_{zz} = -2$, reaching 1.5%
- min for $P_{zz} = 1$, reaching -0.75%

For the deuteron one can achieve $-1.5 \lesssim P_{zz} \lesssim 0.7$ which yields

$$-0.5\% \lesssim v_2\{\Phi_P\} \lesssim 1\%$$

With the present accuracy of flow measurements could be measured!

Fixed target experiments - easier to polarize

“Conventional” eccentricity

Usually the ellipticity of the fireball in each event is evaluated with respect to its principal axis Ψ_2,

$$\epsilon_2 e^{i\Psi_2} = -\frac{\int \rho d\rho d\alpha \, e^{2i\alpha} f(\vec{\rho})\rho^2}{\int \rho d\rho d\alpha \, f(\vec{\rho})\rho^2}$$

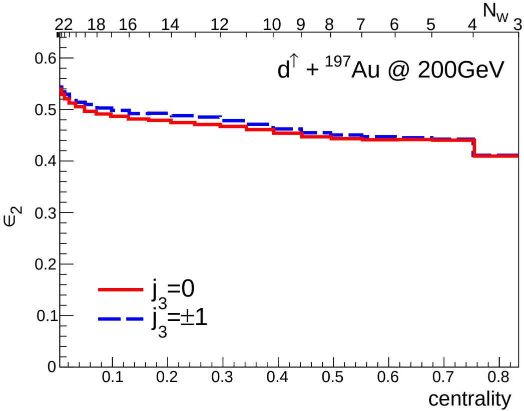
ϵ_2 fluctuates from event to event, and so does the orientation of the event plane Ψ_2

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos\left[2(\phi - \Psi_2)\right]$$

To extract v_2, methods involving two-particle correlations must be used

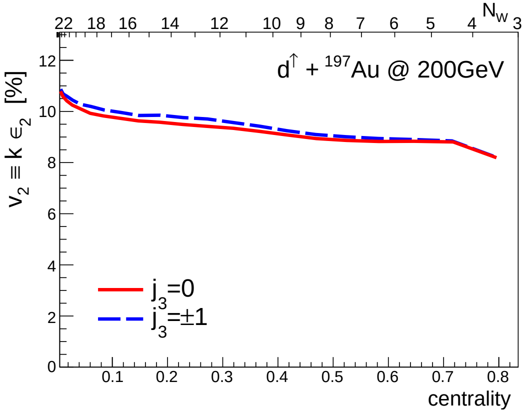
The observable we propose involves the one-body distribution – simpler

“Conventional” eccentricity



dominated by fluctuations, small relative effect

"Conventional" eccentricity



dominated by fluctuations, small relative effect

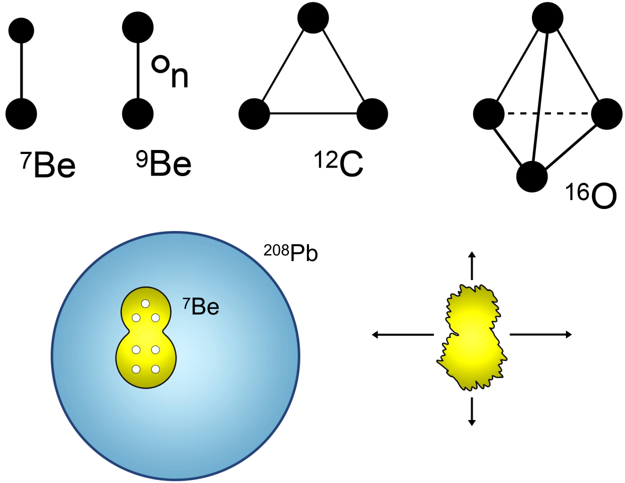
Other nuclei

We expect a similar or larger size of $\epsilon\{\Phi_P\}$ for heavier nuclei with $j \geq 1$. A rough measure of the admixture of $L > 0$ states is the mismatch of the total magnetic moment from the sum of magnetic moments of the nucleonic spins:

nucleus	mismatch
d	3%
^{7}Li	14%
^{9}Be	60%

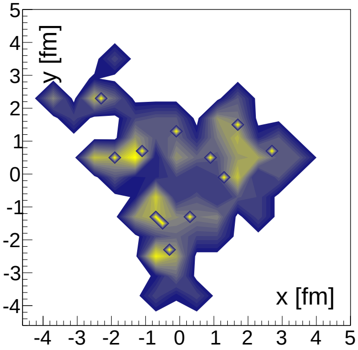
Clusters

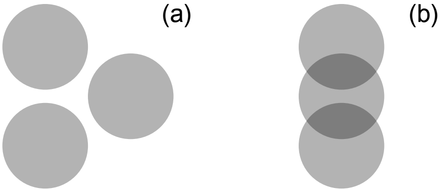
Cluster structure in light nuclei



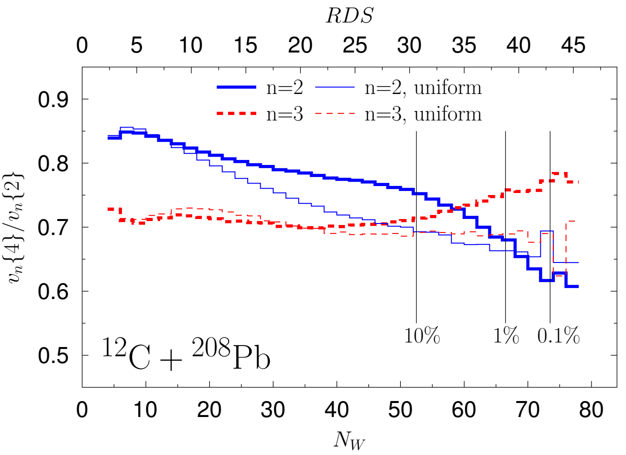
[WB, **Ruiz Arriola** 2013, PB, WB, ERA, **Rybczynski** 2014, WB, MR, **Piotrowska** 2018]

^{12}C





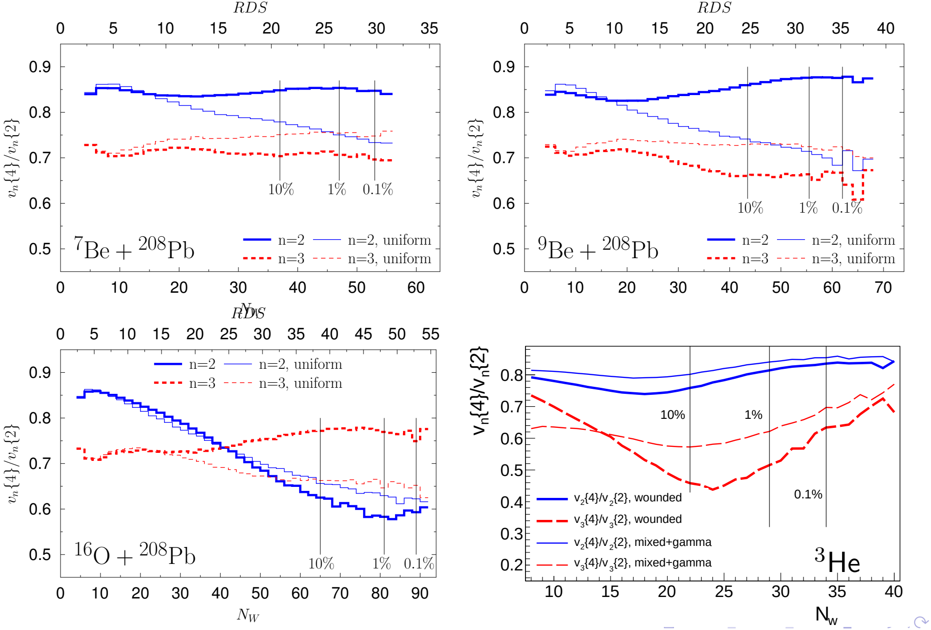
Ratio $v_n\{4\}/v_n\{2\}$ (insensitive to the hydro response)



Ratio for n with geometric component goes up at low c

(RDS=$N_{\rm W}/2 + N_{\rm bin} \sim S$)

Ratio $v_n\{4\}/v_n\{2\}$ (insensitive to the hydro response)



Conclusions

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1. Flow with polarized $j \geq 1$ light nuclei – new proposal to probe the shape-flow transmutation, robust (collectivity)
2. Collisions of light clustered nuclei on heavy targets – qualitative effects and up to 20% quantitative effects for most central collisions