Tuning the initial deformation of a QGP droplet with polarized deuterons

Wojciech Broniowski

Details in Piotr Bożek and WB: PRL 121 (2018) 202301 [arXiv:1808.09840]

2015/19/B/ST2/00937 National Science Centre Poland

Outline

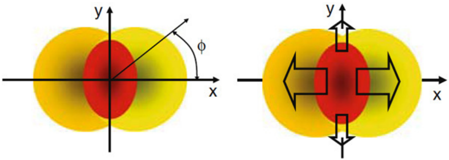
- Collectivity: shape-flow transmutation
- Small systems, d+A
- Polarized deuteron
- Other light nuclei with $j \geq 1$, relation to quadrupole moment
- Experimental prospects

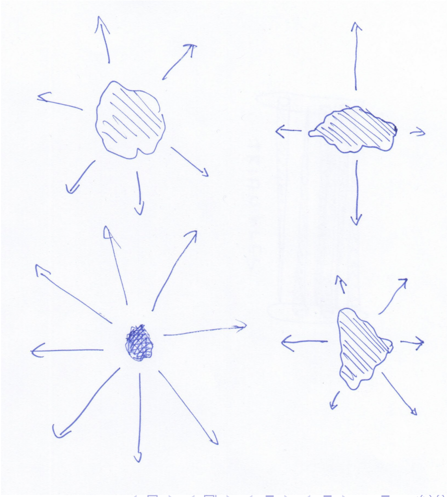
Shape-flow transmutation

Shape-flow transmutation

[Ollitrault '92 . . . Miller, Snellings, 2001 . . .]

Collective response to geometry and fluctuations
many particles, final/intermediate-state interactions, generation of flow

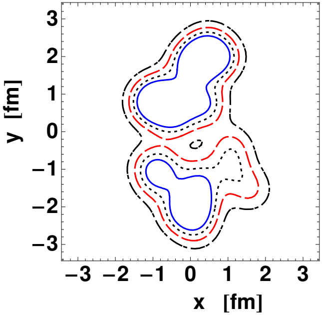


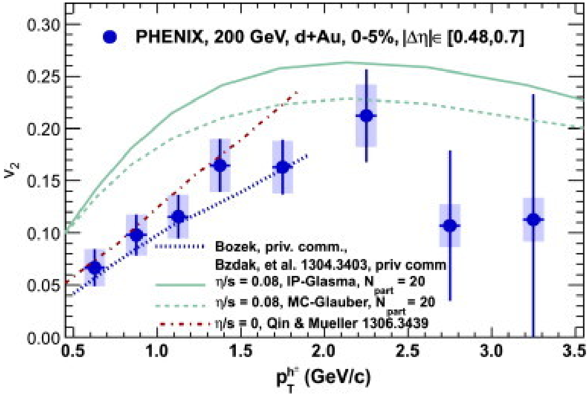


Small systems

d+A

"small" systems [PB 2011]



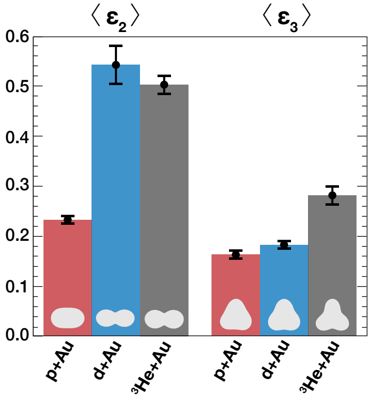


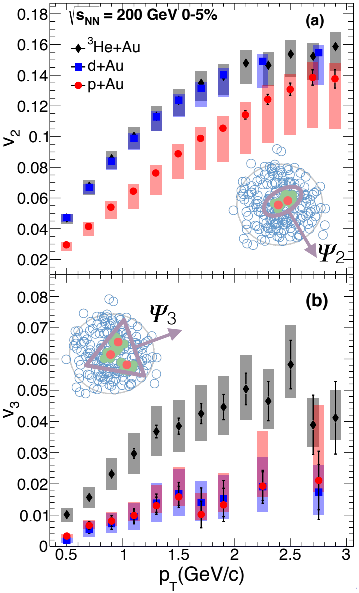
large deformation in d → large eccentricity of geometry

→ large elliptic flow

Flow hierarchy in small systems

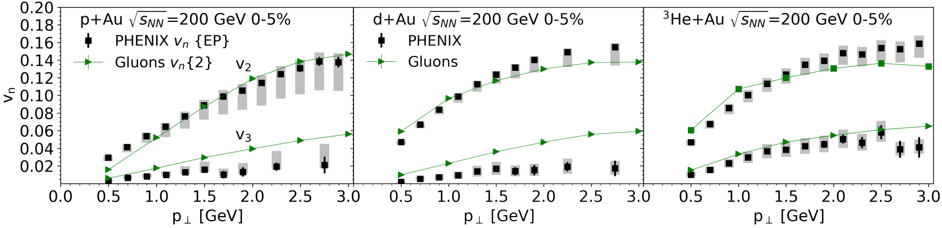
[PHENIX, arXiv:1805.02973]





Color Glass Condensate

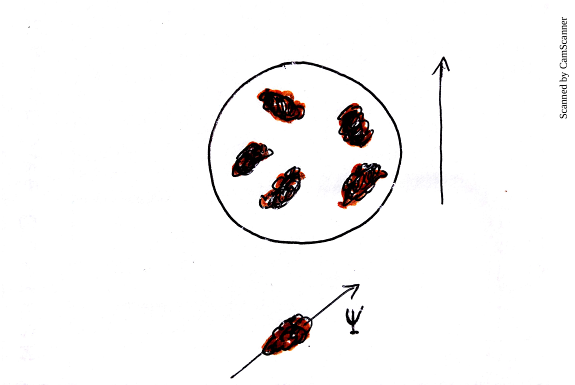
... correlations are predominantly generated from early coherent gluons → one expects that for configurations in high multiplicity d+A collisions color domains around separated projectile neutron and proton contribute independently. Then v_2 in d+A would be smaller than in p+A, contrary to experiment. MSTV: high multiplicity events have larger saturation scales and specific orientation of the deuteron, with one nucleon behind the other (!)
[Mace, Skokov, Tribedy, Venugopalan, PRL 121 (2018) 052301 (1805.09342)]



Questioned in [Nagle, Zajc, arXiv:1808.01276] → controversy

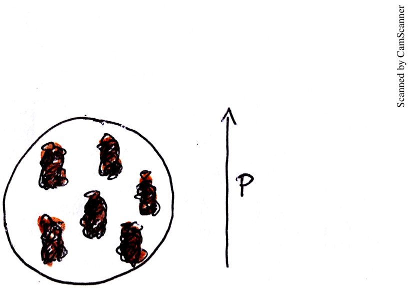
Correlation measurements

No control/knowledge of the principal axis



$$\frac{dN}{d\phi_1 d\phi_2} \propto 1 + 2v_2^2\{2\} \cos\left[2(\phi_1 - \phi_2)\right] + \ldots$$

One-body $v_2\{\Phi_P\}$



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

Advantageous from the experimental point of view

CGC would produce no signal!

Polarized deuteron

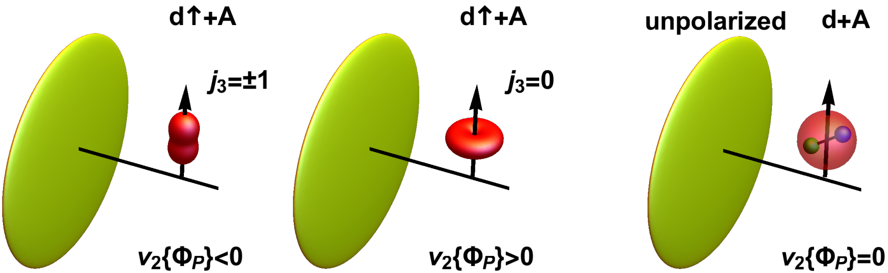
Motivation: hydro vs CGC dispute

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



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

Of course,

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

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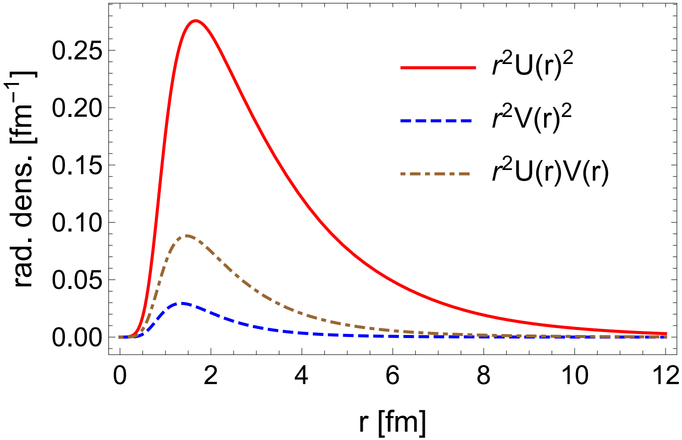


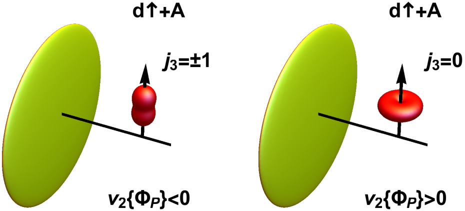
rad. dens. [fm^-1]
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
r [fm]
r²U(r)²
r²V(r)²
r²U(r)V(r)

Ellipticity of $|\Psi|^2$

Ellipticity with respect to a fixed axis at Φ_P for any distribution $f(\vec{\rho})$ is

$$\epsilon_2\{\Phi_P\} = -\frac{\int \rho d\rho d\alpha \cos\left[2(\alpha - \Phi_P)\right] f(\vec{\rho})\rho^n}{\int \rho d\rho d\alpha f(\vec{\rho})\rho^n},$$

$\vec{\rho}$ – transverse coordinate, α – azimuth



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

$$\epsilon_2^{|\Psi|^2_{j_3=\pm 1}}\{\Phi_P\} \simeq -0.47\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} \simeq -0.05$$

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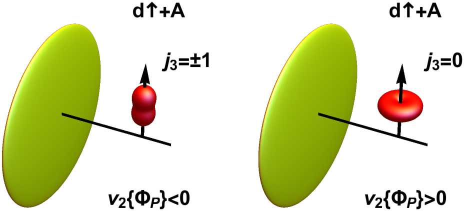
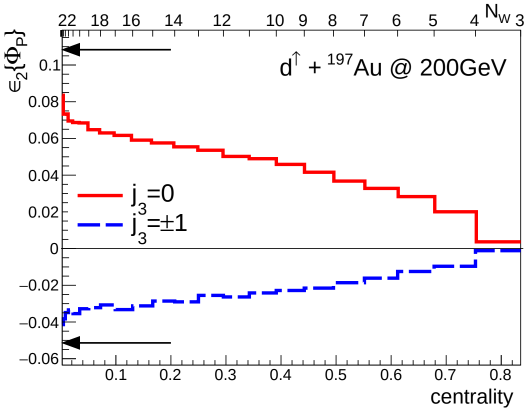


$$\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} = \frac{\int d^3r\, r^2\{\frac{2\sqrt{2}}{5}\cancel{U(r)V(r)} - \frac{1}{5}V(r)^2\}}{\int d^3r\, r^2\{\frac{2}{3}U(r)^2 - \frac{2\sqrt{2}}{15}\cancel{U(r)V(r)} + \frac{11}{15}V(r)^2\}} \simeq \cancel{0.11} - 0.007$$

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

Ellipticity of the fireball relative to polarization axis

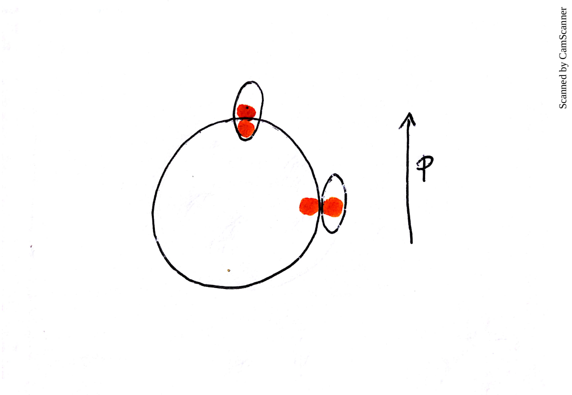
Wounded nucleon model from GLISSANDO



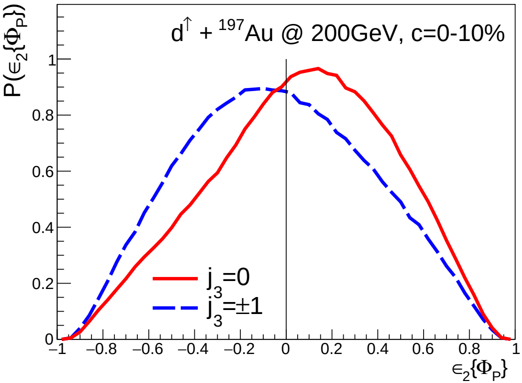
$\sim$30% reduction from $\epsilon_2^{|\Psi|^2}$ (arrows), washing out by nucleons from Au

Dependence on centrality

central - some washing off $\sim 30\%$)
peripheral - two-nucleon case (averages out to 0)



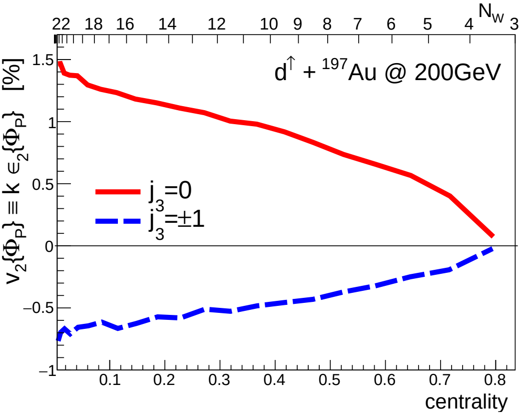
Distribution of the ellipticity of the fireball (most central)



$v_2\{\Phi_P\}$ (relative to the polarization axis)

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

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



$v_2\{\Phi_P\}$ 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

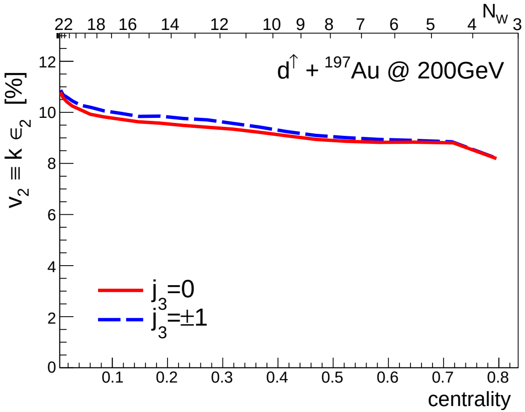
$$-0.5\% \lesssim v_2\{\Phi_P\} \lesssim 1\%$$

With the present accuracy of flow measurements could be measured!

Fixed target experiments - easier to polarize

"Conventional" eccentricity

(evaluated wrt principal axis of the event)



Dominated by fluctuations, small relative effect

Quadrupole moment

Relation of $\epsilon_2\{\Phi_P\}$ to Q_2

Quadrupole moment:

$$Q_2 = \left\langle r^2 \sqrt{\frac{16\pi}{5}} Y_{20}(\Omega) \right\rangle = 2\langle z^2 - x^2 \rangle$$

$$\epsilon_2\{\Phi_P\} \equiv -\frac{\langle z^2 - x^2 \rangle}{\langle z^2 + x^2 \rangle} = -\frac{\langle z^2 - x^2 \rangle}{\langle \frac{2}{3}(z^2 + 2x^2) + \frac{1}{3}(z^2 - x^2) \rangle} = -\frac{3Q_2}{4Z\langle r^2 \rangle + Q_2}$$

Wigner-Eckart theorem (Q_2 is a rank-2 tensor):

$$\langle j j_3 | \hat{Q}_{20} | j j_3 \rangle = \langle j j_3 20 | j j_3 \rangle \langle j || \hat{Q}_2 || j \rangle$$

The lowest possible j is 1 (no effect for ^{3}He or tritium, where $j = \frac{1}{2}$)

Ellipticity estimates based on nuclear data

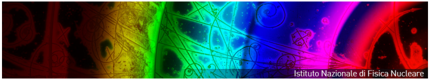
	j	j_3	$\langle r^2\rangle^{1/2}$ [fm]	Q_2 [fm^2]	$\epsilon_2^{\vert\Psi\vert^2}\{\Phi_P\}$ [%]
d	1	± 1	2.1414(25)	0.2860(15)	~ -5
		0		$\times(-2)$	~ 10
^{7}Li	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.4	~ -4	~ 15
		$\pm\frac{1}{2}$		$\times(-1)$	~ -15
^{9}Be	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.5	~ -5	~ -15
		$\pm\frac{1}{2}$		$\times(-1)$	~ 15
^{10}B	3	± 3	2.5	~ 8.5	~ -20

Experimental prospects

Experimental prospects

“Easy” flow measurement (one-body), but one needs a polarized target...

SMOG@LHCb



Internal gas target experiments at the LHC

V.Carassiti[1], G.Ciullo[1], P. Di Nezza[2], P.Lenisa[1], L.Pappalardo[1], E.Steffens[3]

[1] University of Ferrara and INFN, [2] INFN - Laboratori Nazionali di Frascati, [3] University of Erlangen

In collaboration with:
R.Engels (fz-juelich), J.Depner (Erlangen), K.Grigoryev (fz-juelich),
E.Maurice (CNRS/IN2P3, Orsay), A.Nass (fz-juelich), F.Rathmann (fz-juelich),
D.Reggiani (PSI-Zurich), A.Vasilyev (Gatchina),

12/09/18

- Elliptic flow in ultra-relativistic collisions with polarised deuterons

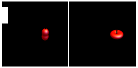
pol

arXiv:1808.09840

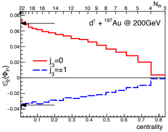
Ridge and flow measurements, connected to collectivity phenomena, are among the most interesting results achieved in the last years in the QGP physics.

We can put this in connection with spin clarifying the nature of dynamics in small systems

its experimental confirmation would prove the presence of the shape-flow transmutation mechanism, typical of hydrodynamic expansion, or rescattering in the later stages of the fireball evolution



ultra-relativistic d+A collision, where the deuteron is polarised along the axis ΦP perpendicular to the beam



Ellipticities of the fireball

A polarised D-beam at BNL will not come in a near future

A polarised target at LHC can easily provide Pb $D^\uparrow$ collisions

Experimental prospects

"Easy" flow measurement (one-body), but one needs a polarized target...

AFTER@LHC

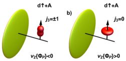
Plans for future fixed target experiments at the LHC

Cynthia Hadjidakis
IPN Orsay, Paris-Sud/Paris-Saclay University, France

Town meeting: Relativistic Heavy Ion Physics
CERN
24 October, 2018

Other opportunities: collective-like effects in Pb-D$^{\uparrow}$

- Intrinsic deformation of polarized (transversally) deuteron → non-zero v_2 in case of collective dynamics (hydro, transport models) wrt transverse target polarisation axis in Pb+D$^{\uparrow}$ for charged particles
- No azimuthal asymmetries expected from the correlation from gluon dynamics (CGC model): powerful probe to discriminate among models



P. Bozek and W. Broniowski. arXiv:1808.09840

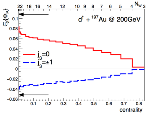


FIG. 3. Ellipticities of the fireball formed in polarized d+Au collisions at the energy of $\sqrt{s_{NN}} = 200$ GeV. The lower coordinate axis shows the centrality as defined via the produced entropy S. The top coordinate axis shows the corresponding number of the wounded nucleons. The arrows indicate the ellipticities of the modulus squared of the deuteron wave function of Eq. (8).

Conclusions

Conclusions

- Flow with polarized $j \geq 1$ light nuclei – new proposal to probe the shape-flow transmutation in small systems
- Basic for understanding the nature of collective correlations: flow or CGC?
- Possible to test in future polarized fixed-target experiments
- Other opportunities:
  1. Hard probes (jets, photons, heavy flavor mesons) could be measured relative to Φ_P
  2. Interferometry correlations could be measured for the same-charge pion pairs emitted in the directions parallel or perpendicular to Φ_P $\rightarrow$ azimuthal asymmetry of the pion emission source in the fireball could be observed