Collective flow in collisions with light polarized nuclei

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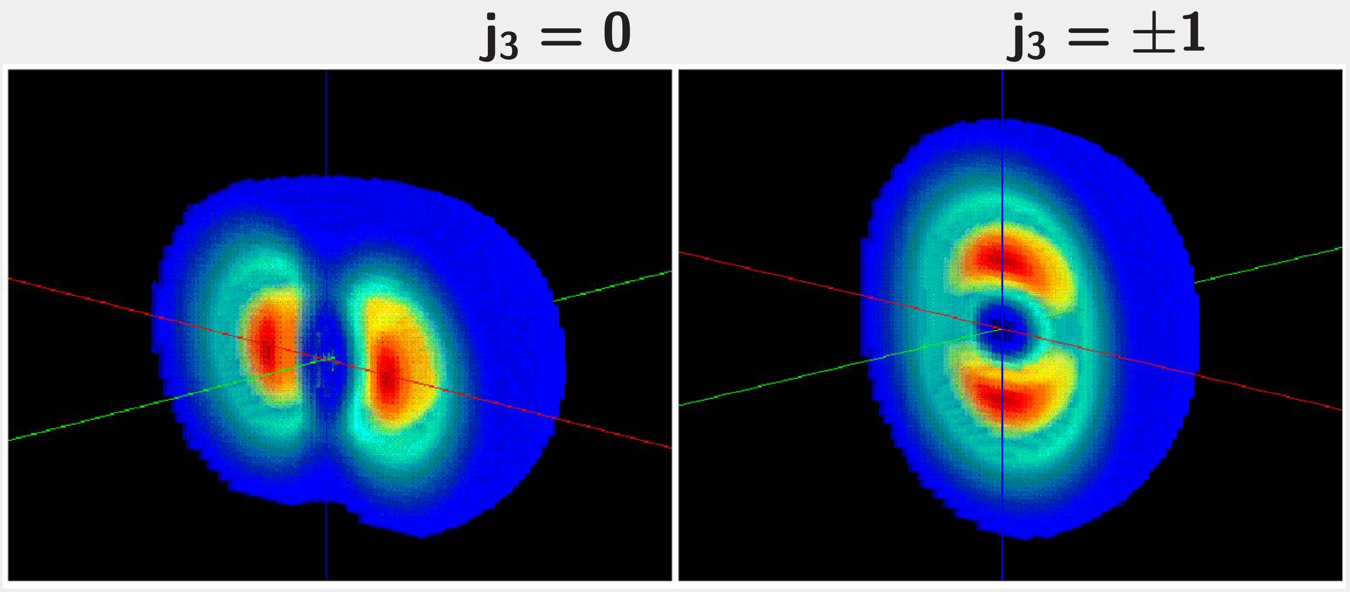
Abstract

We propose to collide light polarized nuclei with a large nucleus. The intrinsic quadrupole deformation of many light nuclei can be controlled using the spin polarization. In such collisions the azimuthal symmetry is broken via polarization of the wave function of the light nucleus, resulting in nonzero one-body elliptic flow coefficient evaluated relative to the polarization axis. Our estimates involve experimentally well known features of light nuclei, such as their quadrupole moment and the charge radius, yielding the one-body elliptic flow coefficient in the range from 1% for the deuteron to 5% for ^{10}B nucleus. Estimates for elliptic flow in collisions of polarized light nuclei with spin $j \geq 1$ with a heavy nucleus are given.

Quadrupole deformation

Light nuclei with spin $j \geq 1$ can have a quadrupole deformation. The deuteron in spin states $j_3 = \pm 1$ or $j_3 = 0$ has a sizable deformation with respect to the polarization axis (due to the 5% admixture of $^3D_1$ wave).

$j_3 = 0$ $\qquad$ $j_3 = \pm 1$



Deuteron densities in two spin states.
(M. Garcon, J. W. Van Orden, Adv. Nucl. Phys. 26 (2001) 293)

Using the deuteron wave function

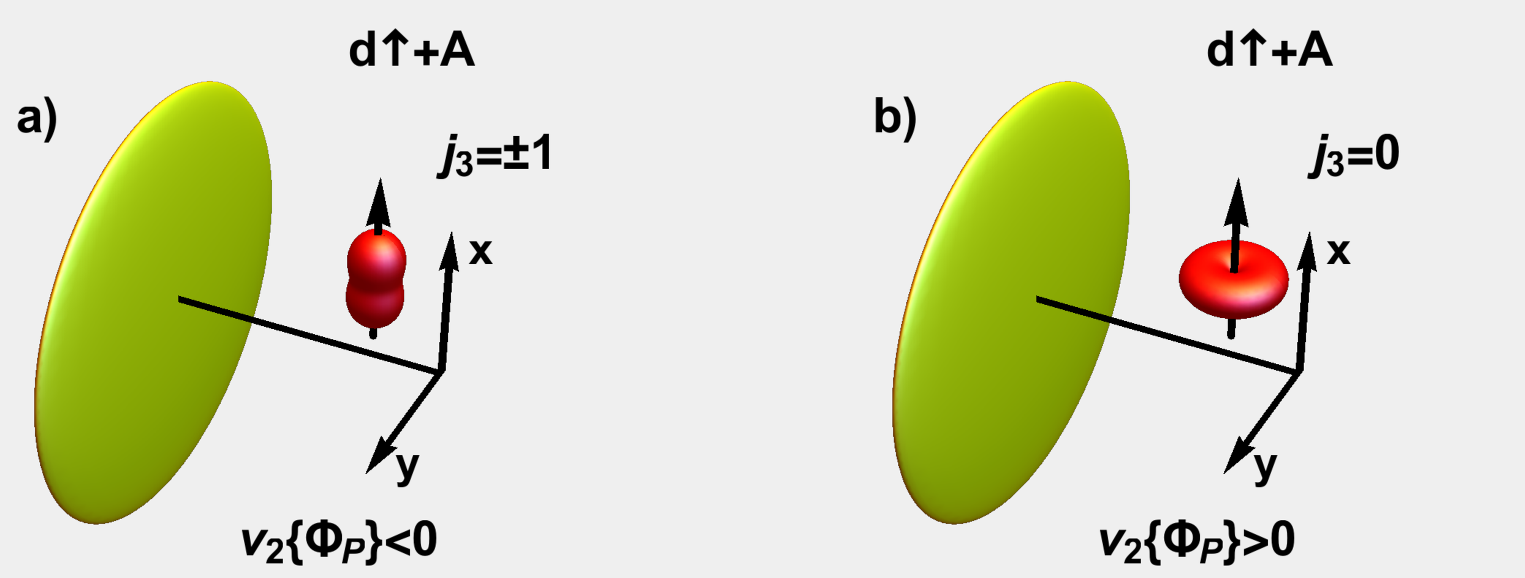
$$|\Psi(r;1)\rangle = U(r)|00\rangle|11\rangle + V(r)\left[\sqrt{\tfrac{3}{5}}|22\rangle|1\,-1\rangle - \sqrt{\tfrac{3}{10}}|21\rangle|10\rangle + \sqrt{\tfrac{1}{10}}|20\rangle|11\rangle\right],$$
$$|\Psi(r;0)\rangle = U(r)|00\rangle|10\rangle + V(r)\left[\sqrt{\tfrac{3}{10}}|21\rangle|1\,-1\rangle - \sqrt{\tfrac{2}{5}}|20\rangle|10\rangle + \sqrt{\tfrac{3}{10}}|2\,-1\rangle|11\rangle\right].$$

The densities are

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

The mixed term $U(r)V(r)$ yields a significant deformation of the densities

$$\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} \simeq 0.1 \qquad \epsilon_2^{|\Psi|^2_{j_3=\pm 1}}\{\Phi_P\} \simeq -0.05$$



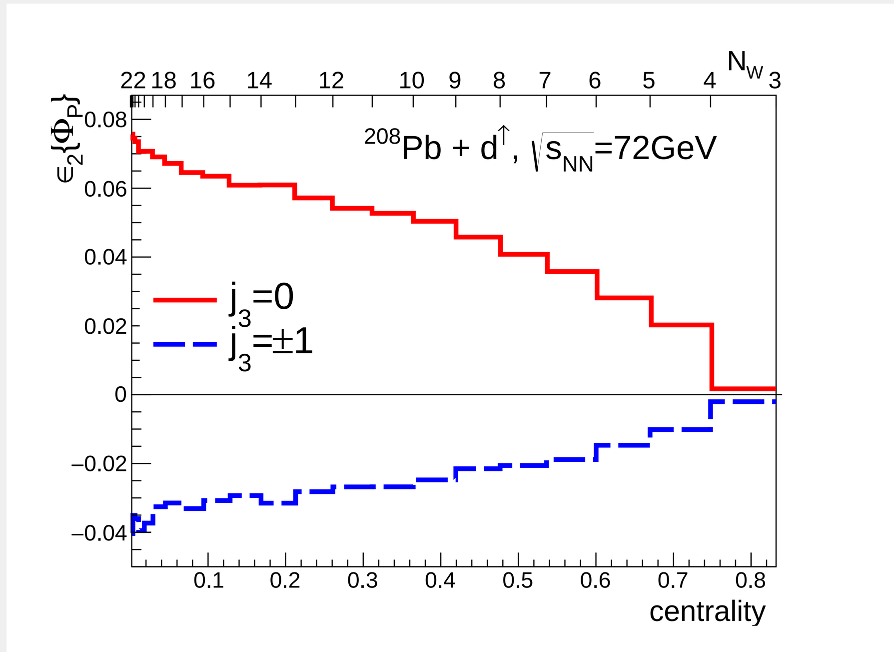
Schematic view of the collision of a polarized deuteron with a large nucleus.

References

[1] P. Bożek, W. Broniowski, Phys. Rev. Lett. 121 (2018) 202301.
[2] W. Broniowski, P. Bożek , arXiv: 1906.09045.

Glauber model and hydrodynamic response

In a collisions with a polarized light nucleus participant nucleons from the large nucleus also contribute to the fireball. The fireball has an elliptic deformation with respect to the polarization axis. The ellipticity is reduced due to the wash-out of the shape (of the order of the average N-N wounding distance).



Ellipticities for LHC experiments on a fixed *polarized* deuteron target

Estimates from the Glauber model give

$$\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} \simeq 0.06 \qquad \epsilon_2^{|\Psi|^2_{j_3=\pm 1}}\{\Phi_P\} \simeq -0.03$$

in central collisions. The initial deformation is transformed to the final elliptic flow via the hydrodynamic response $v_2 \simeq k\epsilon_2$, with $k \simeq 0.2$. The final observed elliptic flow respect to the polarization axis is $v_2\{\Phi_P\} \simeq k\epsilon_2\{\Phi_P\}P_{zz}$. For experimentally accessible target polarizations $-1.5 \leq P_{zz} \leq 0.7\%$ the observed azimuthal asymmetry in the particle emission with respect to the polarization axis is about 1%. This effect is easy to measure as it is a property of the one-particle distribution not a two-particle correlation as in standard collective flow measurements.

Other light nuclei

The same idea can be applied to other small nuclei with quadrupole deformation. The size of the effect can be estimated from nuclear properties (quadrupole deformation Q_2 and charge radius $\langle r^2\rangle$), without explicit knowledge of the wave function. The estimated ellipticities $\epsilon_2\{\Phi_P\} \simeq -\frac{3Q_2}{4Z\langle r^2\rangle}$ are

	j	j_3	$\langle r^2\rangle^{1/2}_{ch}$ [fm]	Q_2 [fm^2]	$-\frac{3Q_2}{4Z\langle r^2\rangle}$ [%]
d	1	± 1	2.1421(88)	0.2860(15)	−5.6
		0		×(−2)	×(−2)
^{7}Li	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.444(42)	−4.03(4)	19
		$\pm\frac{1}{2}$		×(−1)	×(−1)
^{9}Be	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.519(12)	5.29(4)	−17
		$\pm\frac{1}{2}$		×(−1)	×(−1)
^{10}B	± 3	± 3	2.428(50)	8.47(6)	−25
		± 2		×0	0
		± 1		×(−3/5)	×(−3/5)
		0		×(−4/5)	×(−4/5)

The final estimate for the elliptic flow in differently spin states is

$$v_2\{\Phi_P\} \simeq -k\frac{3Q_2}{4Z(\langle r^2\rangle + \frac{3}{2}\langle b^2\rangle)}\frac{3j_3^2 - j(j+1)}{j(2j-1)}$$

(b is the N-N wounding distance in the Glauber model). The predicted signal is stronger for nuclei with larger quadrupole deformation. The model predicts a specific dependence on the spin state (Wigner-Eckart theorem).

Conclusions

A new experimental signature of collectivity in small systems is proposed. In collisions with light polarized nuclei the deformation of the fireball with respect to a fixed axis can be controlled. In the presence of collective flow particle emission is azimuthally asymmetric. This observable is not sensitive to non-flow correlations. (Project supported by the Polish National Science Centre grant 2018/29/B/ST2/00244)