Effects of nuclear Deformation in Heavy Ion Collisions.

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OUTLINE:

• Introduction to Nuclear Deformation
  → many interesting pieces, oblate, prolate...

• Collisions of deformed nuclei
  → eccentricity, elliptic flow, fluctuations....

• Conclusions...
Quadrupole deformation: Theoretical Calculation

Moller Chart of Nuclides 2000
Quadrupole Deformation

Pb-204 $\rightarrow$ Hg-200 + $\alpha$
$10^{17}$ years
Woods-Saxon Density.

\[ \rho_w(x, y, z) = \frac{\rho_o}{1 + e^{(r - R_o(1 + \beta_2 Y_{20} + \beta_4 Y_{40}))/a}} \]

- Deformation parameters:
  - quadrupole: \( \beta_2 \rightarrow [3\cos^2(\theta) - 1] \approx Y_{20} \)
  - octupole: \( \beta_3 \rightarrow [5\cos^3(\theta) - 3\cos(\theta)] \)
  - higher order: \( \beta_4 \rightarrow [35\cos^4(\theta) - 30\cos^2(\theta) + 3] \approx Y_{40} \)
  - Highest order: \( \beta_6 \rightarrow \text{nucl-ex/0106023} \)

- see old ref. Rev.Mod.Phys.30 pp.498-506 (1958)
Oblate/prolate shape: $\beta_2$

- $\beta_2 > 0 \rightarrow$ rugby-ball (prolate) shape. Ne-20, Cu-63, Sm, W, U..

- $\beta_2 < 0 \rightarrow$ oblate (squeezed) shape: Si, As, Ge, Au

$\beta_2 = -0.47 \quad \beta_2 = -0.3 \quad \beta_2 = 0.0$
Higher-order deformation: $\beta_4$
Octupole deformation: $\beta_3$

- Pear-shaped deformation
  → under investigation, unstable to $\alpha$-decay
- Two candidates: Sm-149 and Rn-222
  $(\beta_3 = -0.05) \quad (\beta_3 = -0.13)$
Spherical nuclei = closed shells of nucleon orbitals (magic numbers).

Radius increases as $A^{1/3}$ [assuming constant baryon density].
Shape comparison I.

Ge-70       Sm-154       As-75
Shape comparison II.

W-186  Ga-71  Tm-169
Cf-251 and Th-232

[Cf-251 in RHIC = 89800 Years half-life at 100GeV/n; for $10^{13}$/ beam $\approx$ 1 decay/6s]
Other Pictures II.

\[
\begin{align*}
\text{Ho-165} & \quad \rightarrow \quad \leftarrow \quad \text{Pb-207} \\
\text{(long-polarized)}
\end{align*}
\]
Other Pictures III.

Si-28 $\rightarrow$ ← Au-197
(AGS)
EXOTICS.

Dubnium(105)-268 (16 hours)       REAL-EXOTIC       Americium(95)-240m (1 ms)
**Reality: RHIC Au+Au 200GeV/n**

3-protons, 8-neutrons below 2x-magic Pb.

\[ ^{197}\text{Au} + ^{197}\text{Au} \]

oblate shape\[^{[1]}\]
\[ \beta_2 = -0.13 \]
spin: 3/2
stable, 100%
Natural isotope

Au-197 nucleus Deformation?

Yes: has quadrupole moment \( Q = 0.59 \text{ barn} \) \[ \text{[Phys.Rev.A73(2006)022510]} \]

Other deformed nuclei at RHIC? Yes: Cu-63 & U-238.
Elliptic flow at RHIC energies:
→ origin: the initial *spatial* asymmetry.

For deformed nuclei → initial *eccentricity* is affected !!!
→ elliptic flow is affected.
Optical Glauber Model

- Using Deformed Woods-Saxon density:
  \[ \rho_w(x, y, z) = \frac{\rho_o}{1 + e^{(r-R_o(1+\beta_2 Y_{20} + \beta_4 Y_{40}))/a}} \]
- Projections \([\theta, \phi]\) in transversal plane \(\rightarrow\)
- From the overlap of colliding nuclei:
  - Baryon density
  - \(N_{\text{part}}\): participant density \(\rho_{\text{part}}(x, y)\)
  - \(N_{\text{coll}}\): \(\rho_{\text{coll}}(x, y)\) binary collisions density
- Obtain eccentricity
  \[ \varepsilon = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2} \]
- Multiplicity:
  \[ dN_{\text{ch}}/d\eta = (1 - x) \cdot n_{pp} \frac{N_{\text{part}}}{2} + x \cdot n_{pp} N_{\text{coll}} \]

* Phys. of Atom. Nucl. 71 (2008) 1609
Distributions $N_{\text{part}}$, $N_{\text{coll}}$, $N_{\text{ch}}$ from Opt.GM

Two-component $dN_{\text{ch}}/d\eta$: Phys.Lett.B507(2001)121; $n_{pp} = 2.29$ and $x = 0.13$
Eccentricity in collisions of prolate nuclei.

- Ho-165 ($\beta_2 = +0.3$)

\[ \varepsilon_{\text{part}} = \frac{\sqrt{(\sigma_y - \sigma_x)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2} \]

- Pear-shaped overlaps!

- Fluctuations $\varepsilon[\theta^1,\phi^1;\theta^2,\phi^2]$ at given $[b]$
Technical detail: Random orientation of nucleus.

**Random orientation:**

= random distribution of points where main axis (spin) crosses the surface of the sphere.

Probability is proportional to the area.

Area $dS$ corresponding to $d\theta d\phi$ is:

$$dS = R \sin(\theta) \, d\theta d\phi$$

$\rightarrow$ $P(\theta) = \sin(\theta)/2$ (normalized to 1.)

$\rightarrow$ $P(\phi) = \text{const.}$ (random $\phi$ angle)

$\rightarrow$ angle $\theta$ is not random.

Random orientation means random $\phi$, and $\sin(\theta)$ distributed $\theta$ angle.
Eccentricity in collisions of oblate nuclei.

- Au-197 (predicted $\beta_2 = -0.13$)

Zero eccentricity at $b=3\text{fm}$ and non-zero $\varepsilon$ for $b=0\text{fm}$

Eccentricity fluctuates again!
Deformation of nuclear shape increases

\[ \varepsilon \rightarrow v_2 = \text{Elliptic flow fluctuations.} \]

(at given fixed collision centrality).
What happens with $<\varepsilon>$ due to deformation in UU & AuAu?

- In noncentral collisions $<\varepsilon>$ stays unchanged
  
  → central coll: Increased $<\varepsilon>$ due to deformation.
  
  + additionally, deformation increases eccentricity fluctuations.
UU collisions from Opt.GM: $dN_{ch}/d\eta$

Only deformation

Deformation + FLUCT

Cusp in $\langle \varepsilon \rangle$ for very-central collisions (large $dN_{ch}/d\eta$).

Highest multiplicity: $dN_{ch}/d\eta$ is observed for longitudinally polarized, central $b=0$ fm collisions.

$\rightarrow$ eccentricity cusp $\leftarrow$
Why \( \frac{dN_{\text{ch}}}{d\eta} \) sensitive to orientation?

\[ \frac{dN_{\text{ch}}}{d\eta} \text{ depends on orientation due to } N_{\text{coll}} \]

\[ dN_{\text{ch}}/d\eta = (1 - x) \cdot n_{pp} \frac{N_{\text{part}}}{2} + x \cdot n_{pp} N_{\text{coll}} \]

- \( N_{\text{part}} \) is not sensitive to orientation \( v_2 \) \( [N_{\text{part}}] \) not interesting.

\[ \rightarrow \text{ Study: } v_2 [dN_{\text{ch}}/d\eta] \text{ (in central collisions)!} \]
Eccentricity fluctuations:
\[ \sigma_\varepsilon = \sqrt{\sigma_{\beta^2}^2 + \tilde{\sigma}_\varepsilon^2} \]
→ finite number of interacting nucleons: \( \tilde{\sigma}_\varepsilon \)
→ ground-state deformation of coll. nuclei: \( \sigma_{\beta^2} \)

Effects predicted by Optical Glauber Model → **confirmed.**
Comparison of Entropy Density in Au+Au vs. U+U

Entropy density: \[ \rho_s(x, y) = \kappa_s \left[ \alpha \rho_{\text{part}}(x, y) + (1 - \alpha) \rho_{\text{coll}}(x, y) \right] \]

**$\beta_4$ deformation Parameter for $^{238}$U**

- Moller et al. [1] prediction for $^{238}$U is: $\beta_4 = +0.093$
  - spatial distribution of nucleons is modified
  - participant eccentricity is modified
  - final $\nu_2$ strength can be modified! [hydro calc. needed].

$^{238}$U participant density in transversal plane [fm$^{-2}$].

Polarization of $^{238}$U beam? No way.

Spin of $^{238}$U = 0$^+$
Magnetic moment $\mu = 0$
Quadrupole moment: unknown.

$\rightarrow$ consider $^{238}$U beam unpolarized.
CONCLUSIONS:

● Nuclei collided at AGS/SPS/RHIC are deformed:
  → Si-28, Cu-63, In-115, Au-197, (U).

● **Elliptic flow is affected in deformed nuclei collisions:**
  → eccentricity: \(< \varepsilon >\) increased in Au+Au central
  + cusp for Ho+Ho and U+U predicted
  → fluctuations: \(\sigma(\varepsilon)\) increased !

● \(\beta_4\) deform. parameter for \(^{238}\)U is important !

● **Study of deformation effects is needed to understand properties of partonic matter created at RHIC.**