Ultrarelativistic proton-beryllium collisions

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Outline

Message:

Nuclear structure effects can be seen in ultrarelativistic collisions

Light nucleus "hitting a wall"

[WB + Enrique Ruiz Arriola, PRL 112 (2014) 112501, PB+WB+ERA+MR, PRC 90 (2014) 064902]

deformation in light nuclei

$\updownarrow$

harmonic flow in collisions with a heavy nucleus

[see talks by P. Bożek and M. Rybczyński]

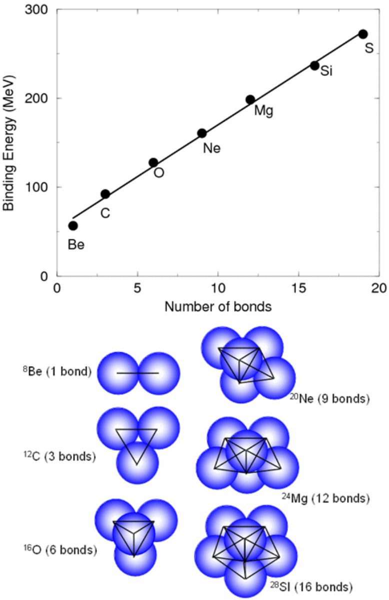
This talk: $p-\mathrm{polarized}\ A$ collisions

- Effects of clustering in light nuclei can be seen in a very robust way in distributions of number of participants
- Polarization needed (spin in the ground state + magnetic field)

Isotopes of beryllium

symbol	Z	N	lifetime	decay	J^P
^{7}Be	4	3	53 days	e capture	$3/2^-$
^{8}Be	4	4	7×10^{-17} s	α	0^+
^{9}Be	4	5	stable		$3/2^-$

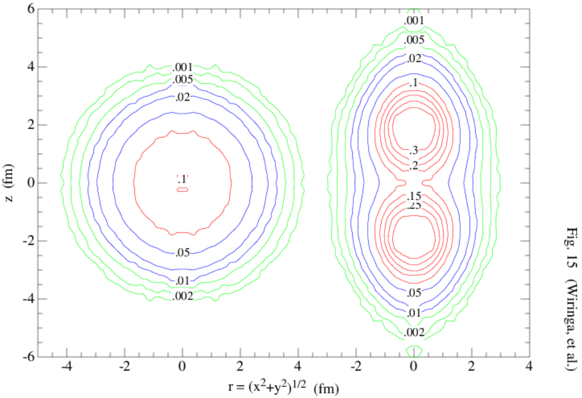
Clusters in light nuclei



- strong binding
- small overlap
- $\rightarrow$ can treat approximately as elementary
- specific excitation spectra
- fragmentation experiments
- Generalization: ^{7}Be=^{4}He+^{3}He, ^{9}Be=2^{4}He+n

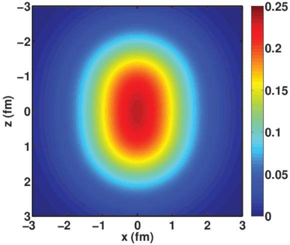
[see C. Beck ed., *Clusters in Nuclei*, Lecture Notes in Physics 818, 848, 875, Springer (2010, 2012, 2014)]

Ab initio ^{8}Be

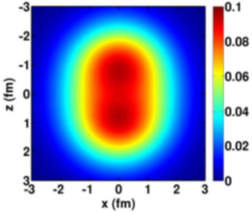


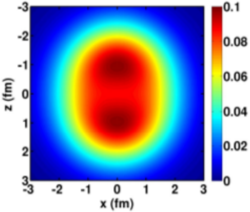
laboratory frame intrinsic frame

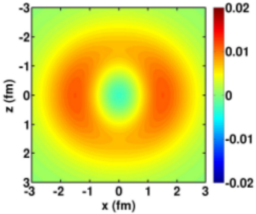
Contours of constant density for ^{8}Be, plotted in cylindrical coordinates. [R. Wiringa et al., PRC 62 (2000) 014001]



^{7}Be $(p+n)$







^{9}Be $\begin{pmatrix} p & n \\ n-p & \end{pmatrix}$

[Robert Chase Cockrell, PhD Thesis, Iowa State U.]

Making states with good quantum numbers

Simplest case: ^{8}Be. GS is a 0^{+} state (rotationally symmetric w.f.).
Deformation concerns multiparticle correlations between the nucleons

Superposition over orientations:

$$|\Psi_{0^+}(x_1,\ldots,x_8)\rangle = \frac{1}{4\pi}\int d\Omega \Psi_{\rm intr}(x_1,\ldots,x_8;\Omega)$$

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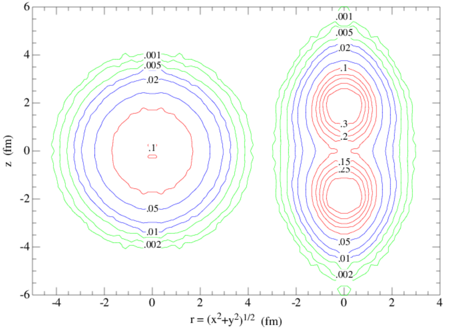

Fig. 15 (Wiringa, et al.)

Making ^{7}Be with good quantum numbers

$^7\text{Be} = {}^4\text{He} + {}^3\text{He}$ (treated as elementary)

$\frac{3}{2}^- = 0^+ \ + \ \frac{1}{2}^+ + 1^-$ (orbital motion of ^{4}He and ^{3}He)

$|\frac{3}{2}, m = \frac{3}{2}\rangle = |\frac{1}{2}, \frac{1}{2}\rangle \otimes |1, 1\rangle$

$|\frac{3}{2}, m = \frac{1}{2}\rangle = \sqrt{\frac{2}{3}}|\frac{1}{2}, \frac{1}{2}\rangle \otimes |1, 0\rangle + \sqrt{\frac{1}{3}}|\frac{1}{2}, -\frac{1}{2}\rangle \otimes |1, 1\rangle$

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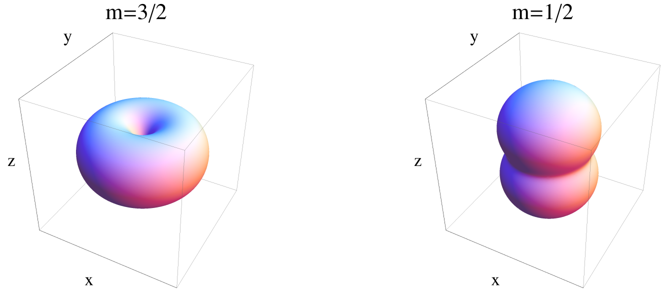
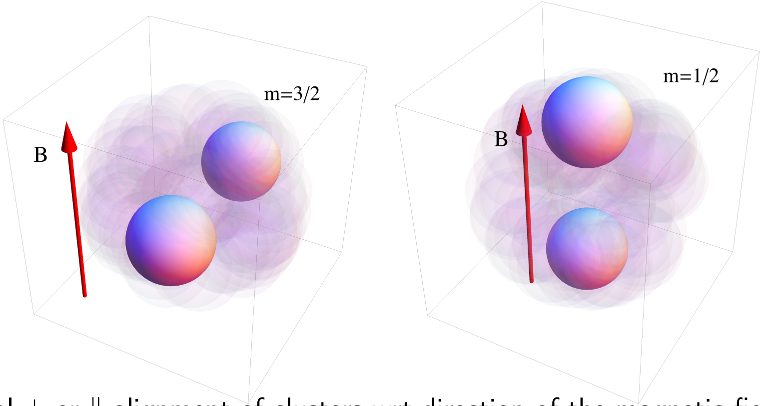


spatial density of orbitals $\left|\langle\frac{3}{2}, m|\frac{3}{2}, m\rangle\right|^2$

Overlaying the intrinsic distributions

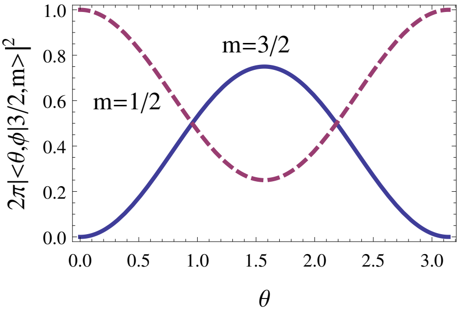
For nuclear physicists: equivalent to the Peierls-Yoccoz projection

$$\Psi_{3/2,m}(\vec{r}) = \sum_{k=\pm\frac{1}{2}} \int d\Omega D^{3/2}_{m,k}(\Omega)\Psi^{\rm intr}_{k}(\vec{r};\Omega)$$



(partial $\perp$ or $\parallel$ alignment of clusters wrt direction of the magnetic field)

Distribution in the axial angle



$m = 3/2$ peaks at the equator ($\perp$), and $m = 1/2$ at the poles ($\|$)

^{9}Be with good quantum numbers

^{9}Be = n + ^{4}He + ^{4}He
$\frac{3}{2}^{-} = \frac{1}{2}^{+} + 0^{+} + 0^{+} + 1^{-}$ (orbital motion of ^{4}He and ^{4}He)

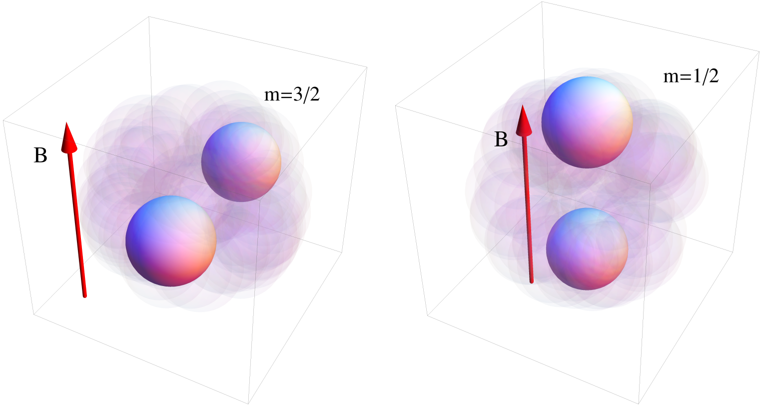
– then the projection is exactly as for ^{7}Be

p – polarized Be collisions

p–^{7}Pb collisions

Why ultra-relativistic?

Reaction time is much shorter than time scales of the structure
$\rightarrow$ a frozen "snapshot" of the nuclear configuration



Glauber framework

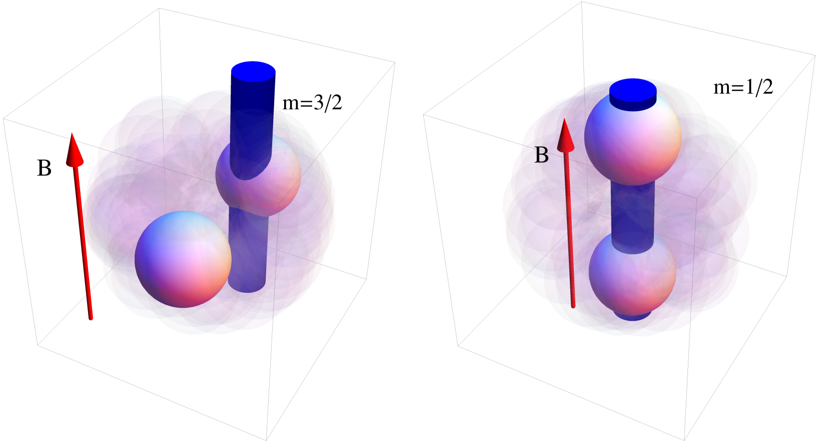
Probability of inelastic p-A interaction at impact parameter $\vec{b}$:

$$
\begin{aligned}
P_{pA}(\vec{b}) &= \prod_{i=1}^{A} \int d^3 x_i \, |\psi_A(\vec{x}_1, \ldots, \vec{x}_A)|^2 \\
&\times \frac{1}{\sigma_{pA}^{\rm inel}(s)} \left\{ 1 - \prod_{i=1}^{A} \left[1 - \sigma_{NN}^{\rm inel} P_{NN}(\vec{b} - \vec{x}_{i,T}) \right] \right\}
\end{aligned}
$$

(correlated) GS wave function enters

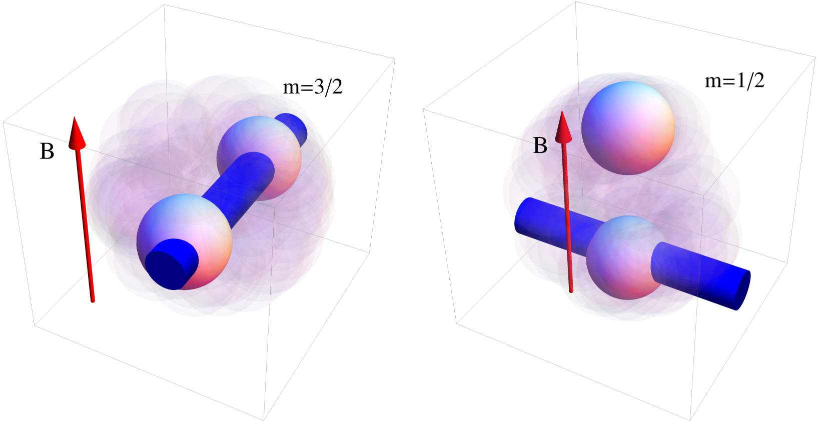
Simulations with GLISSANDO 2, $\sigma_{NN}^{\rm inel} = 32$ mb (SPS)

$B \parallel z$

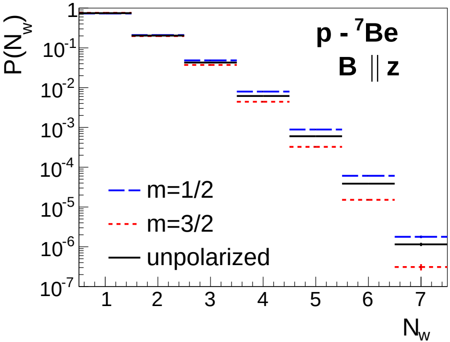


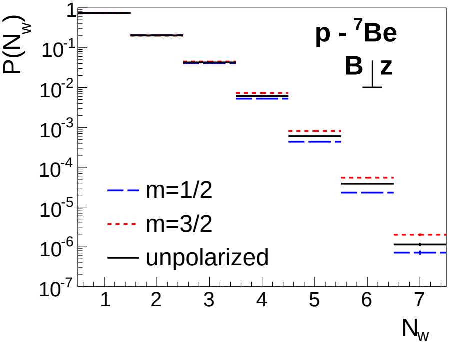
(radius of the cylinder corresponds to the NN wounding cross section)

$B \perp z$

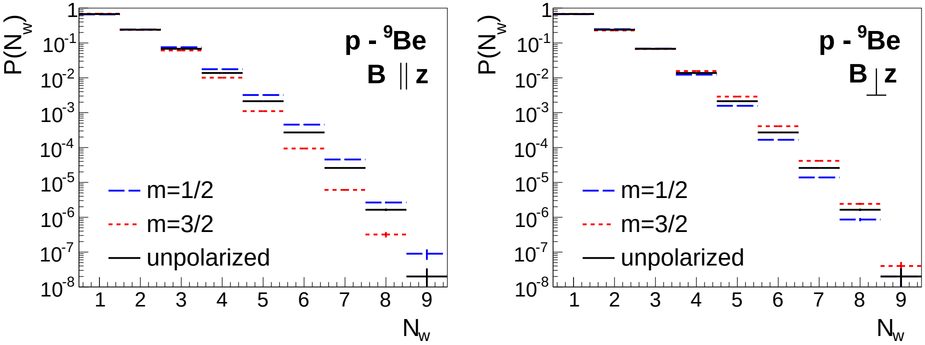


Results for p – ^{7}Be

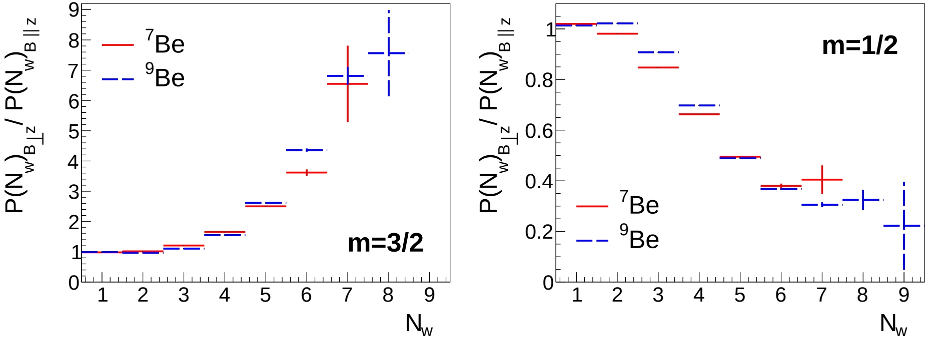




Results for p – ^{9}Be



Ratios



Conclusions

Light nuclei structure from relativistic collisions with protons

- High-energy protons probe the nuclear wave function

Needed: magnetic field → sensitivity to orientation

- Factor-of-a-few effects in the distribution for large N_w
- Need to distinguish m or the orientation wrt magnetic field
- Sensitivity to the nuclear structure: clustering gives the strong effects
- Applicable to nuclei with nonzero spin in GS
- No polarization of Be → small effects (clustered vs uniform: ∼50%)
  – MSc Theses by Milena Sołtysiak, UJK (2014)
- No polarization in Be-Be collisions → small effects

Experimental prospects? There is magnetic field in beam lines ...