Correlations in a bose-bose and bose-fermi helium *s*-wave scattering halo

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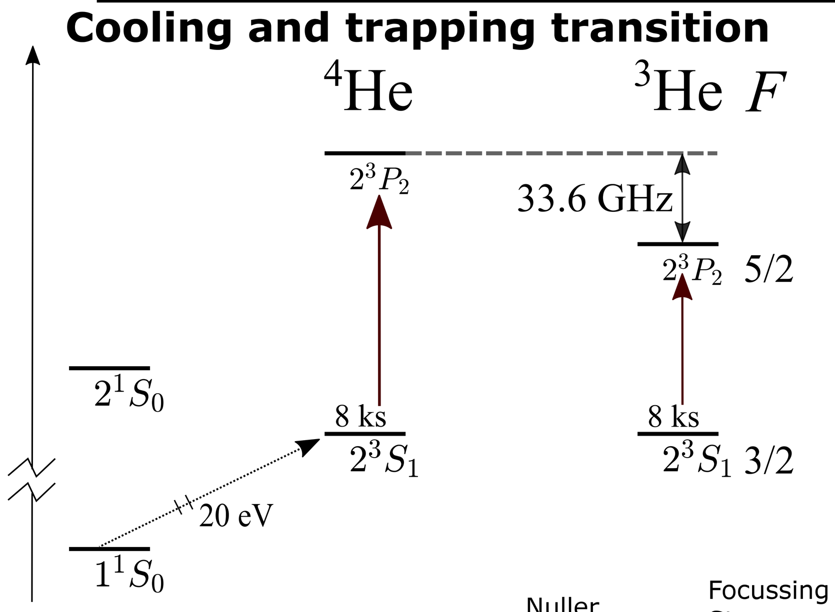
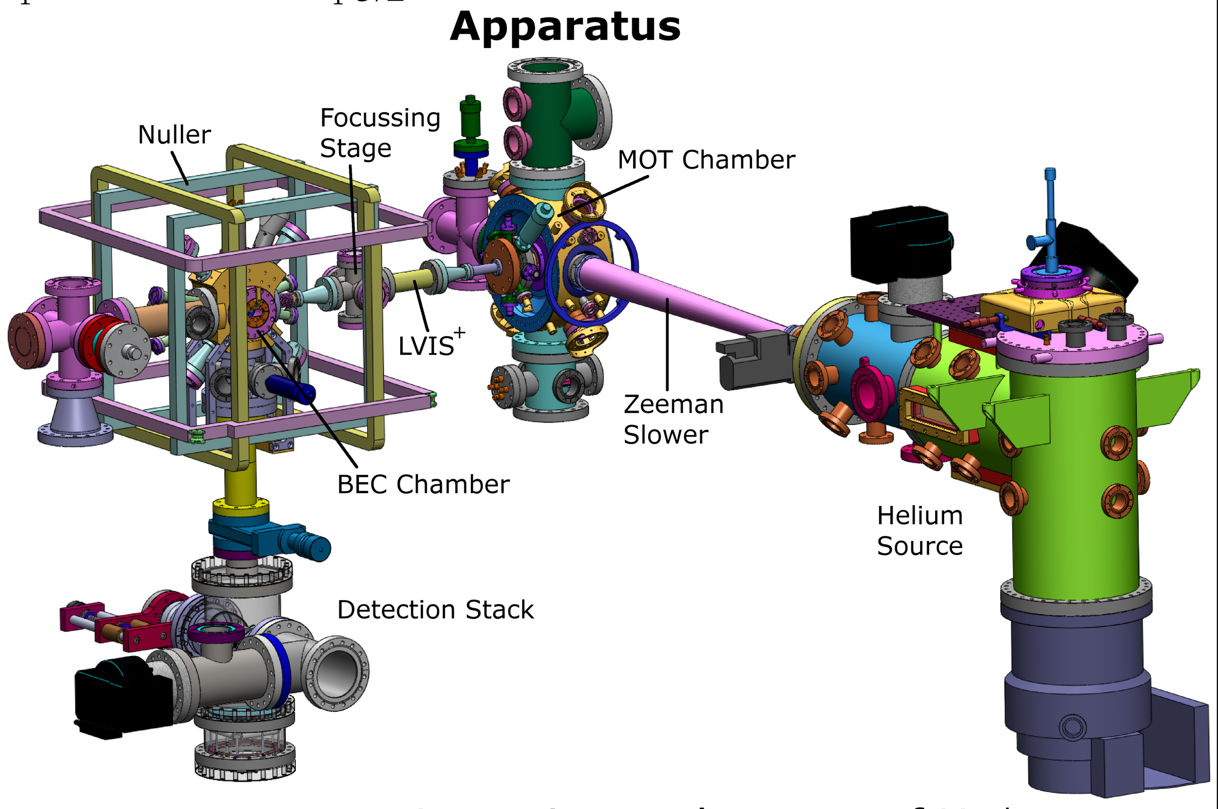
Ultracold ^{3}He*-^{4}He*



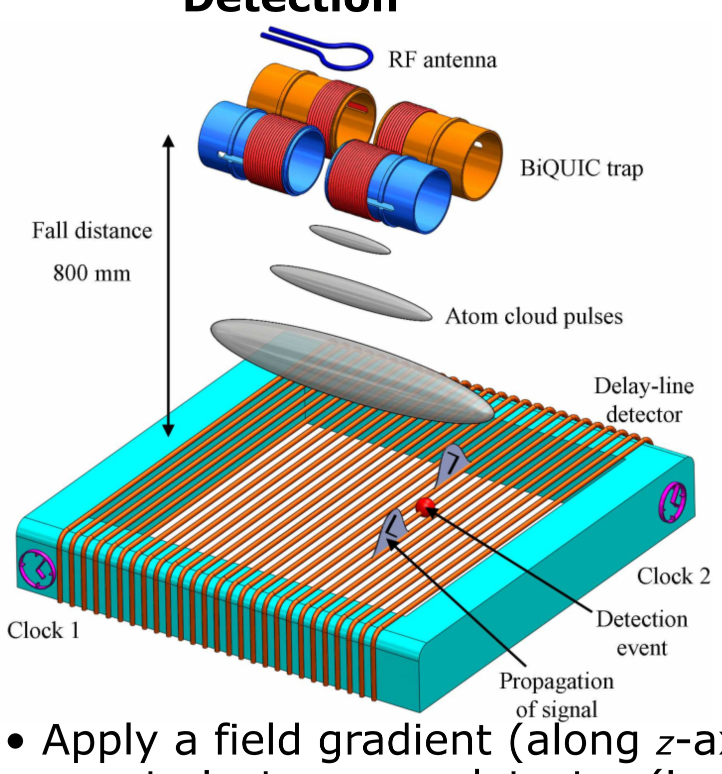
- Metastable ^{3}He and ^{4}He (He*) atoms are trapped in long lived 2^3S_1 excited state
- Same electronic structure except for the nuclear spin of ^{3}He, causing a 33.6 GHz detuning.

Apparatus

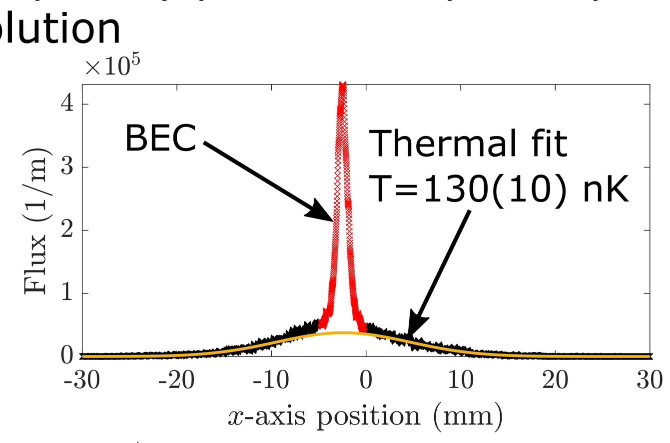


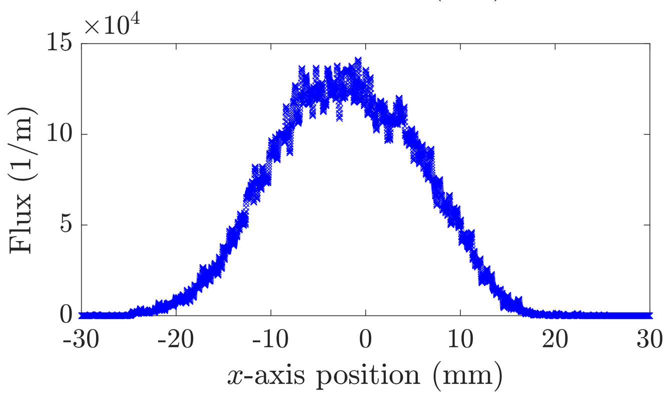
- ^{4}He atoms cooled to <1μK using laser cooling and trapping + magnetic trap and evaporative cooling
- ^{3}He atoms cooled using laser cooling and trapping + sympathetically with ^{4}He

Detection



- Large internal energy of He* atoms allows single atom detection using electron multipliers (for both isotopes)
- Micro-channel plate and delay-line detector allows full 3D detection in far-field (~ momentum) after 416ms fall time
- 100μm x-y position, 10μs temporal resolution





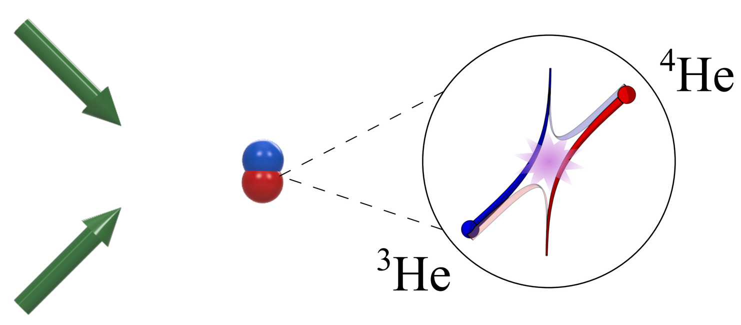
- Apply a field gradient (along z-axis) to separate isotopes on detector (in arrival time)
- Below critical temperature (~1 mK)

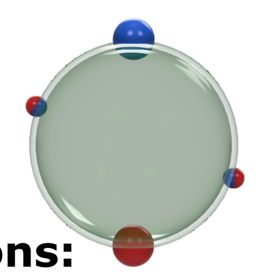
^{4}He = Bose-Einstein Condensate (BEC): all atoms in coherent ground state (equivalent of a laser)

^{3}He = Degenerate Fermi Gas (DFG): all energy states below Fermi energy have an occupancy of one, and zero otherwise.

Bose-Fermi Halo

We can create a collision halo between ^{3}He and ^{4}He, and hence generate a mass entangled state.





Possible uses:
-Investigate nonequlibrium properties of bose-fermi mixtures
-Measure correlations between fermion-boson scattering events
-Observe novel phenomena including: quantum phase transitions; and pairing of fermions and formation of composite particles.

$$|\Psi\rangle \approx \frac{1}{\sqrt{2}}\left|^4He,\, ^3He\right\rangle + \left|^3He,\, ^4He\right\rangle$$

Correlations:
(a) fermion-boson nonlocal correlation
(b) fermion-fermion local antibunching (Pauli exclusion principle)
(c) boson-boson local antibunching due to the correlation with fermionic partner.

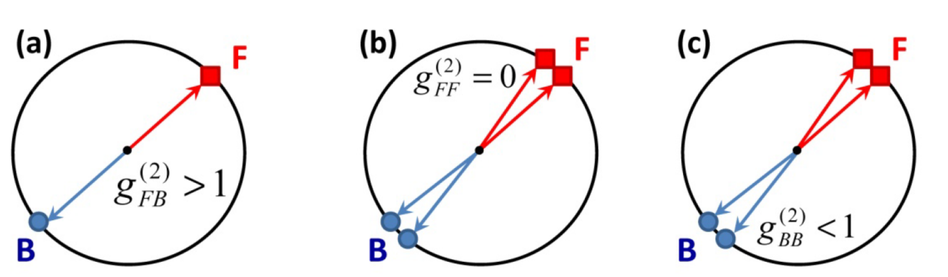


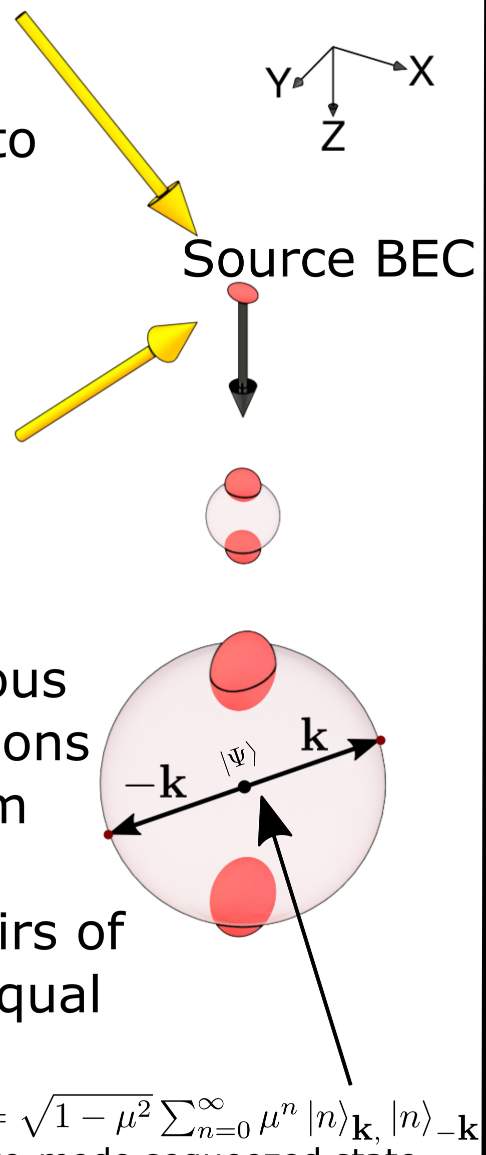
Fig. 4. Diagram of various correlation measurements between representative fermionic (F, squares) and bosonic (B, circles) atoms on the s-wave scattering sphere.

Collision Halo

Defintion: A collision halo is sphereical shell of correlated atom pairs generated by colliding BECs.

Generation

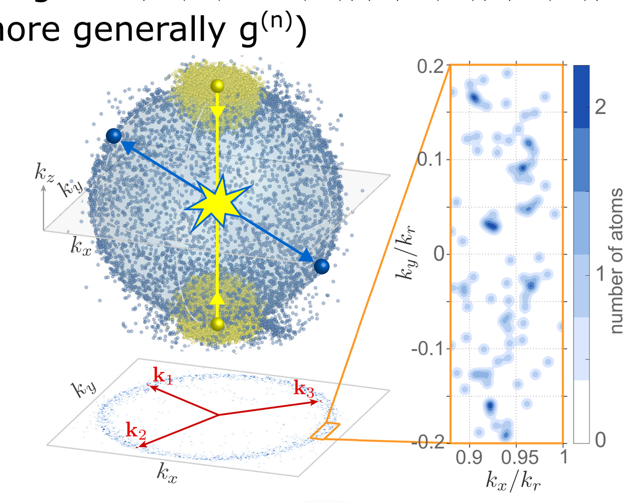
1. Bragg diffraction splits BEC into different momentum modes
2. Modes separate as they freely evolve
3. Spontaneous *s*-wave collisions between atom pairs create entangled pairs of atoms with equal and opposite momenta $|\Psi\rangle = \sqrt{1-\mu^2}\sum_{n=0}^{\infty}\mu^n |n\rangle_{\mathbf{k}} |n\rangle_{-\mathbf{k}}$

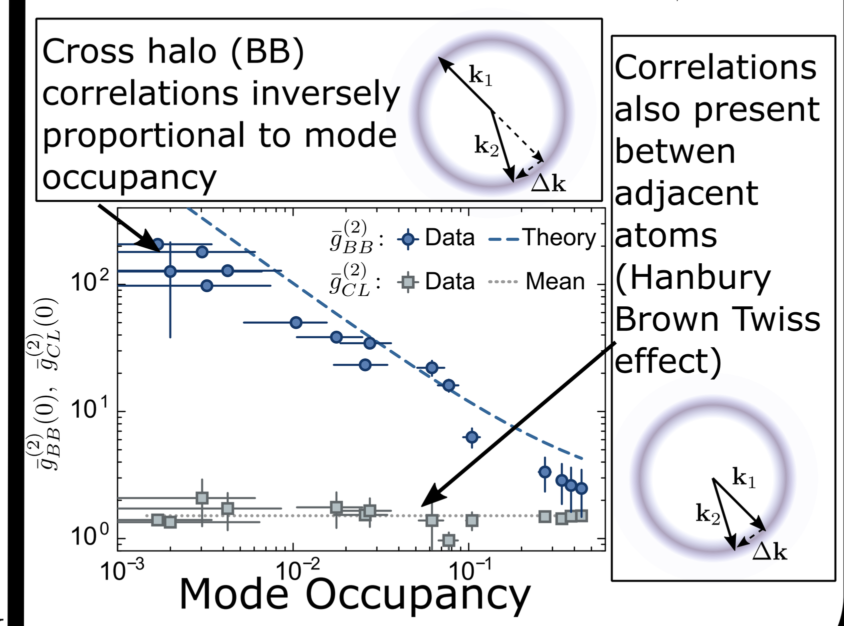


Two-mode sequeezed state

Analysis

Information about manybody wavefunction is encoded in the momentum correlation function $g^{(2)} = \langle N(k_1) \times N(k_2)\rangle / \langle N(k_1)\rangle \langle N(k_2)\rangle$ (and more generally $g^{(n)}$)





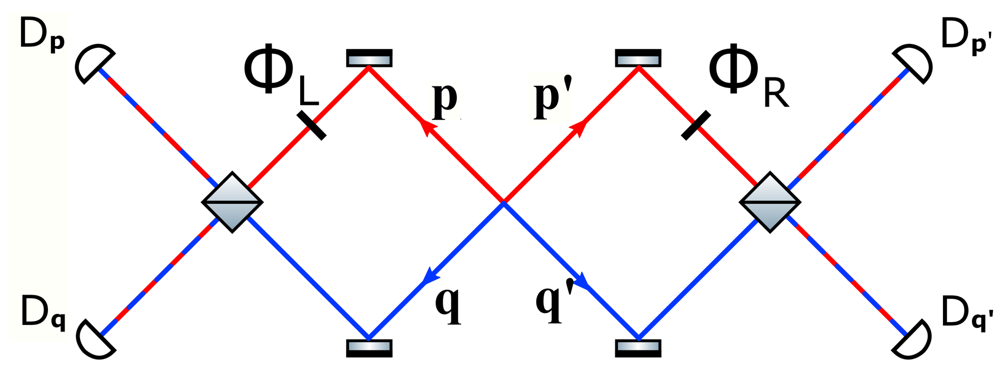
Correlations also present betwen adjacent atoms (Hanbury Brown Twiss effect)

Hodgman, et. al. Phys. Rev. Lett. 118, 240402 (2017)

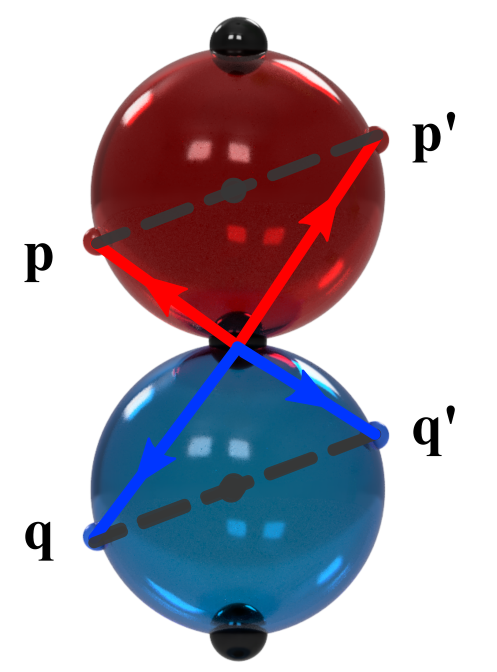
Halo Interferometer

We employ scattering halos entanglement and geometry to create an atomic analogue of a Rarity-Tapster interferometer.

Optical Rarity-Tapster

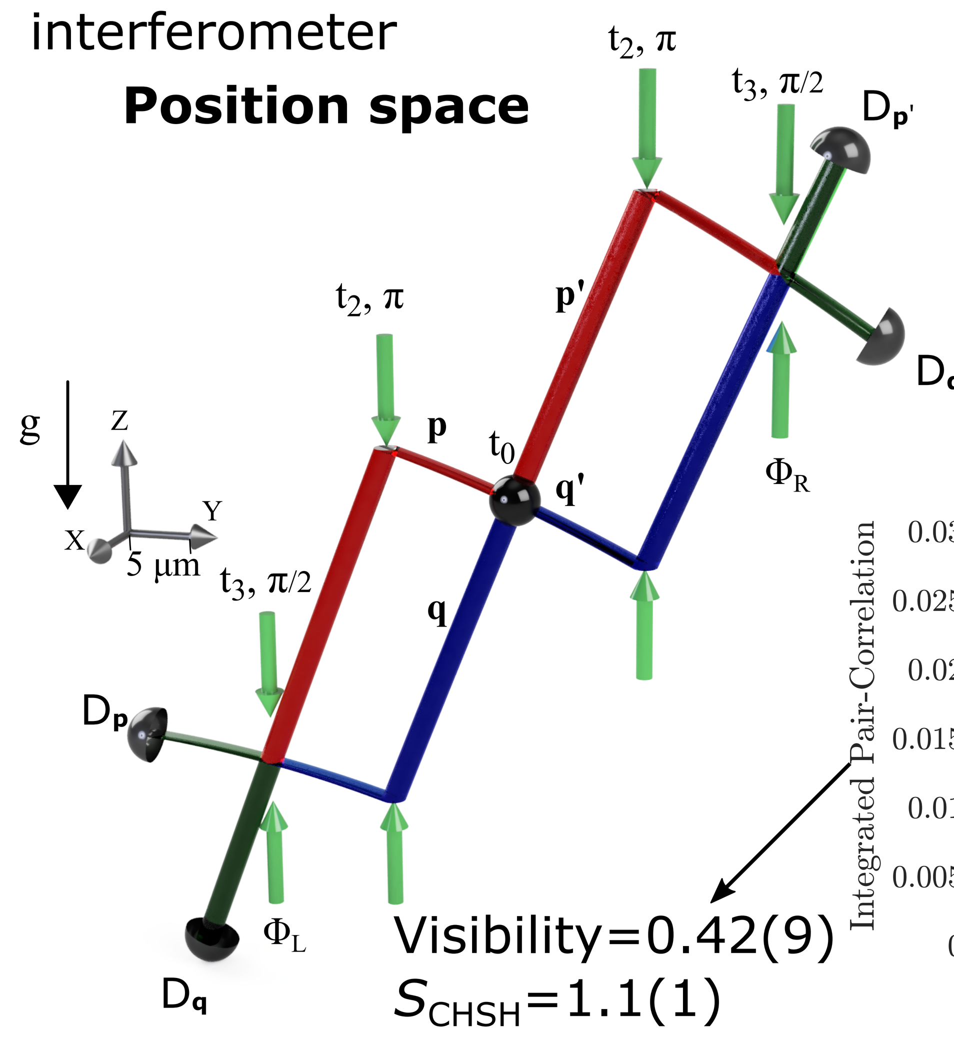


Momentum space



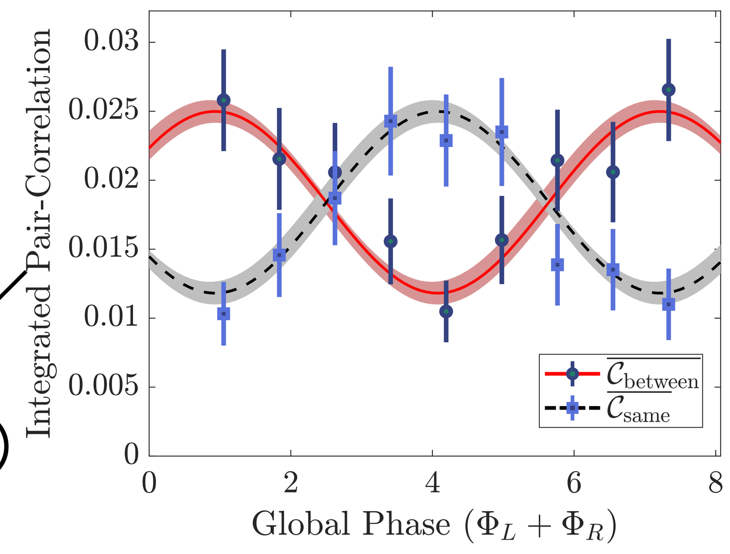
1. Generate two independent halos by splitting BEC into 3 momentum components
2. Apply a sequence of Bragg pulses which couple selected modes into Rarity-Tapster like interferometer

Position space



$$|\Psi\rangle \approx \frac{1}{\sqrt{2}}|\mathbf{q},\mathbf{q}'\rangle + |\mathbf{p},\mathbf{p}'\rangle$$

3. We vary the phase of the beamsplitter pulse and measure the correlation between momentum modes.



Visibility=0.42(9)
S_{CHSH}=1.1(1)

Goal: to use this interferometer to demonstrate a Bell violation using the momentum states of massive particles.