A Degenerate Mixture of ^{3}He* and ^{4}He* with 3D single particle resolution

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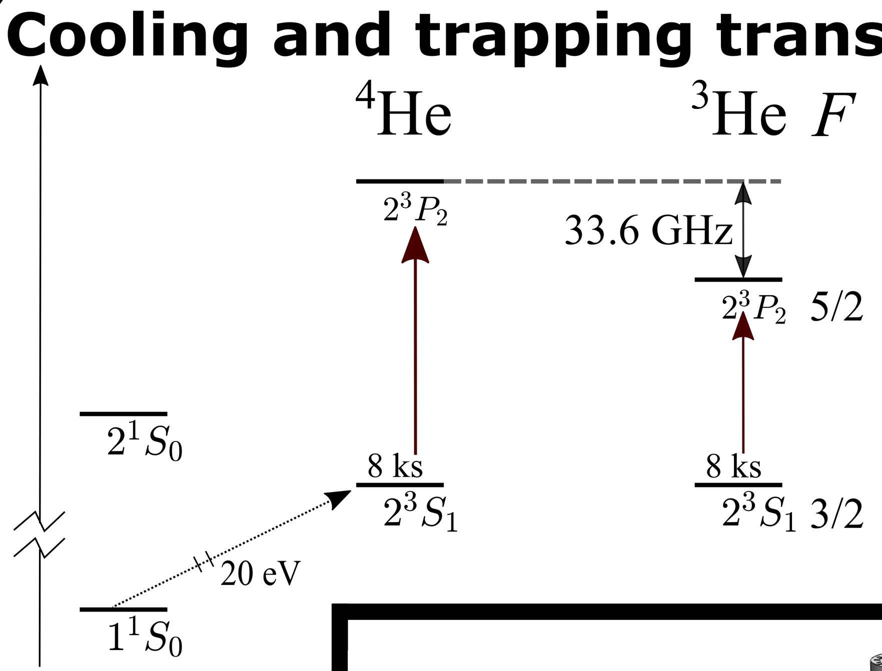
Ultracold ^{3}He*-^{4}He*

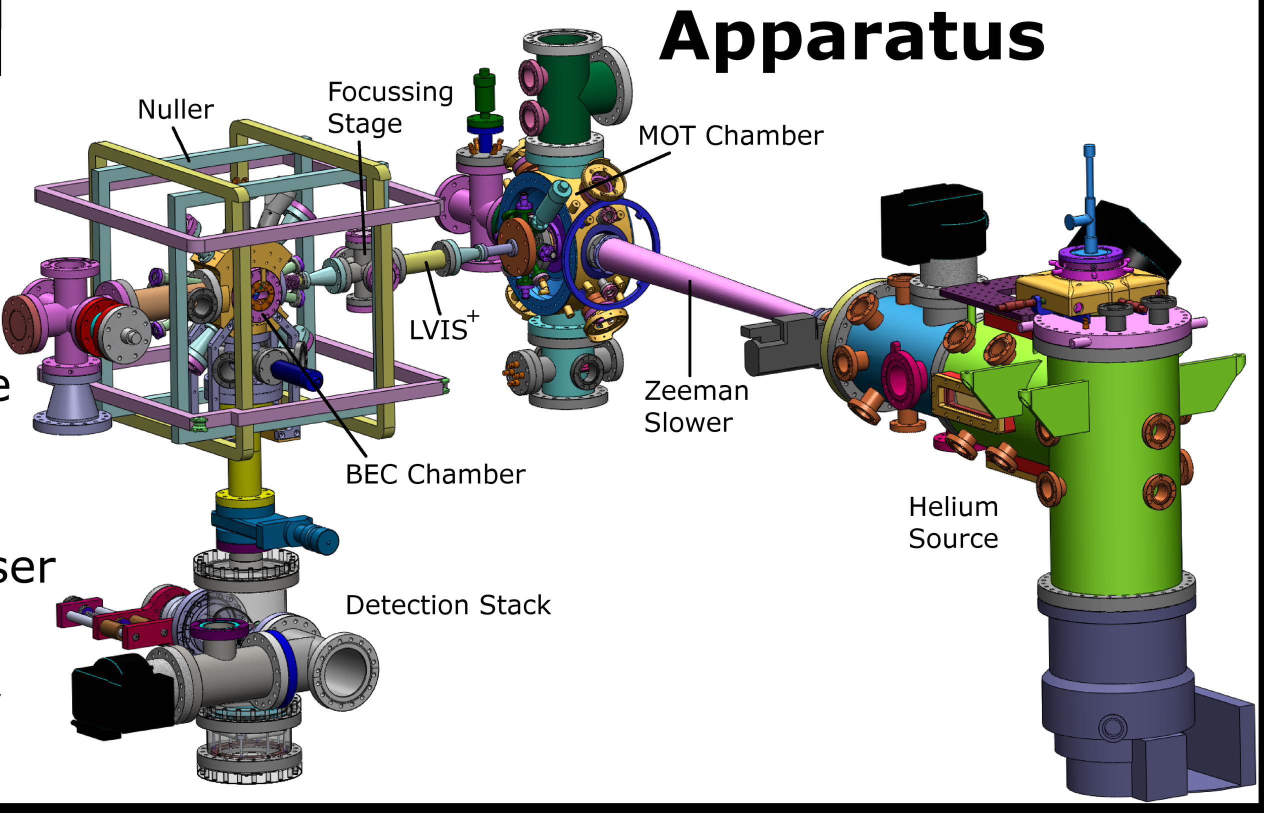
Cooling and trapping transition



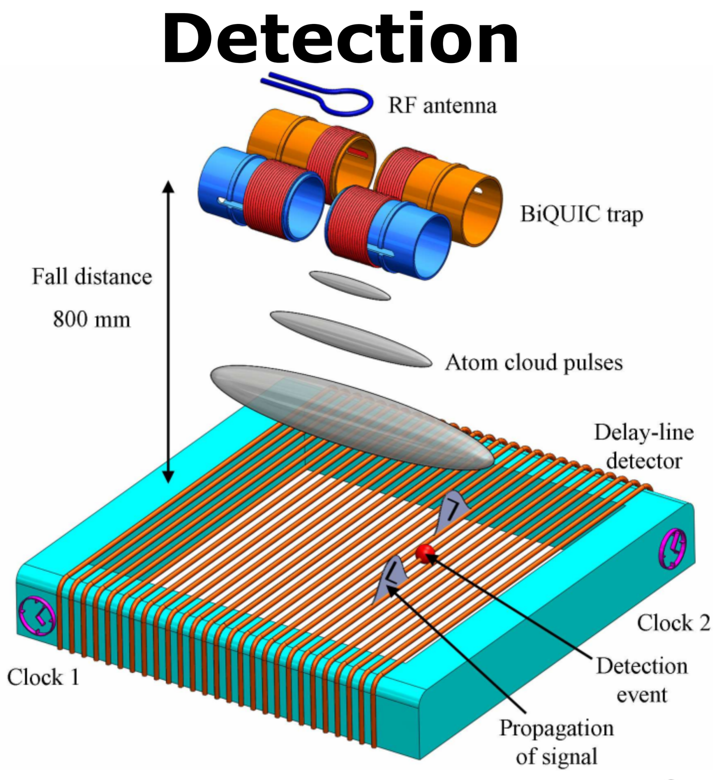
- Metastable ^{3}He and ^{4}He (He*) atoms are trapped in long lived 2^3S_1 excited state
- Same electronic structure except for the nuclear spin of ^{3}He, causing a 33.6 GHz detuning.

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

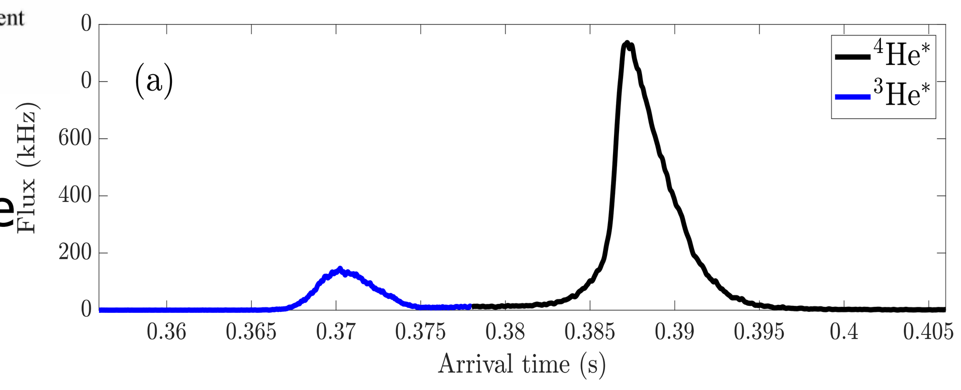


Detection



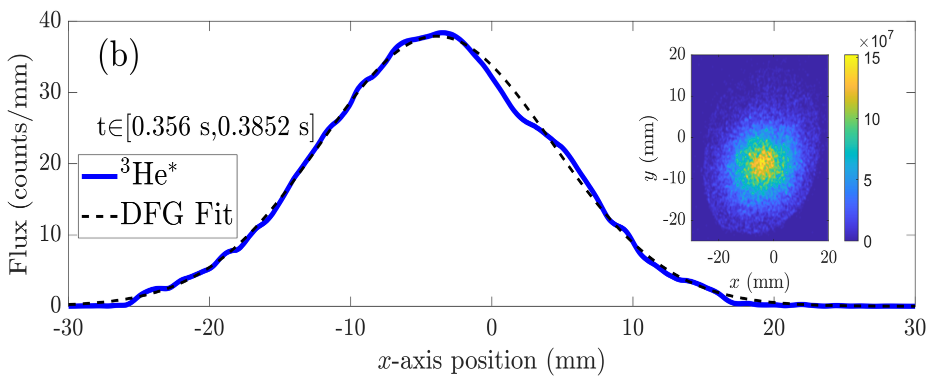
- Large internal energy of He* atoms allows single atom detection using electron multipliers (for both isotopes)
- Micro-channel plate and delay-line detector allows full 3D detection in far-field (~ momentum) after 416ms fall time
- 100μm x-y position, 10μs temporal resolution

- Apply a field gradient (along *z*-axis) to separate isotopes on detector (in arrival time)

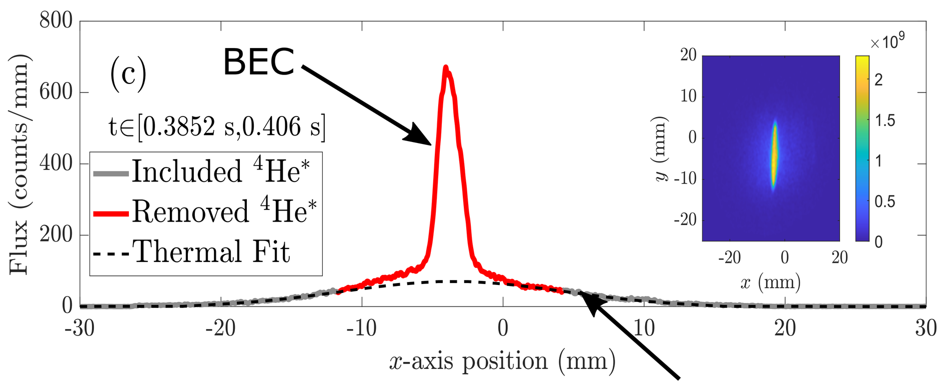


- Below critical temperature (~1 mK)

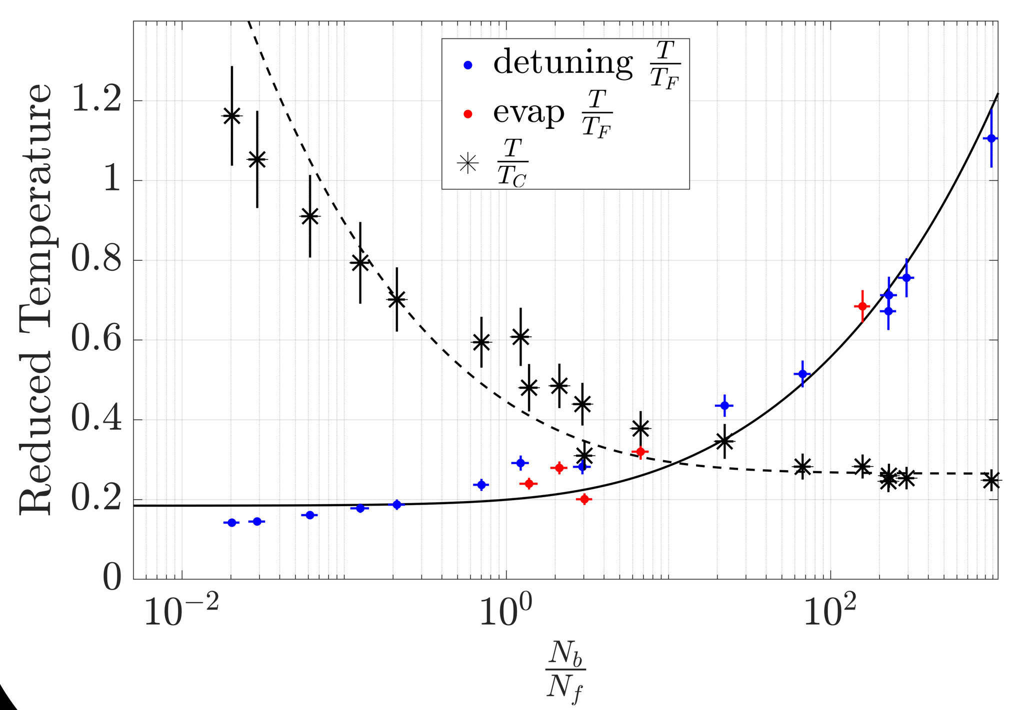
^{3}He = Degenerate Fermi Gas (DFG): all energy states below Fermi energy have an occupancy of one, and zero otherwise.



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



Thermal fit
T=130(10) nK



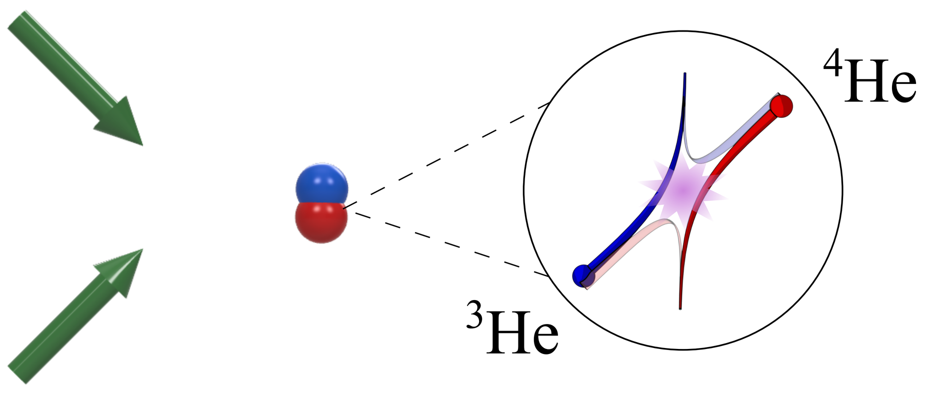
Reduced temperaturs of DFG and BEC depends only on ratio of fermions being sympathetically cooled (N_f) to the final number of bosons (N_b).

Bose-Fermi Collision

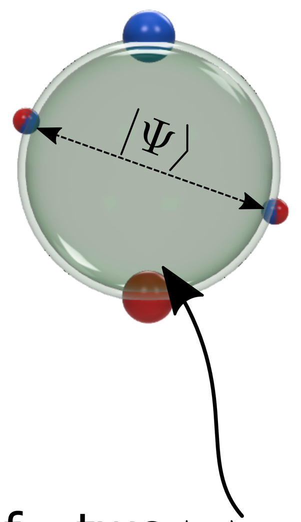
Defintion A collision halo is sphereical shell of correlated atom pairs generated by colliding BECs. We can create a collision halo between ^{3}He and ^{4}He, and hence generate a mass entangled state.

Generation

1. Bragg diffraction splits BEC into different momentum modes



2. As the BEC and DFG separate Spontaneous s-wave collisions between atom pairs



3. Once the BEC and DFG are fully separated we have a spherical shell of entangled pairs of atoms with equal and opposite momenta.

4. The exact state of two diametrically opposed modes is a two-mode squeezed state.

$$|\Psi\rangle = \sqrt{1-\mu^2}\sum_{n=0}^{\infty}\mu^n\,|n\rangle_{\mathbf{k}}\,|n\rangle_{-\mathbf{k}}$$

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

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.

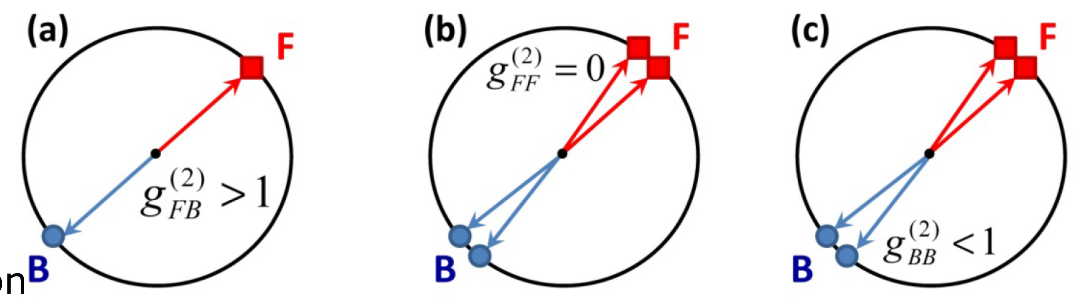


Fig. 4. Diagram of various correlation measurements between representative fermionic (F, squares) and bosonic (B, circles) atoms on the s-wave scattering sphere.

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.

Fermionic Anti-Bunching

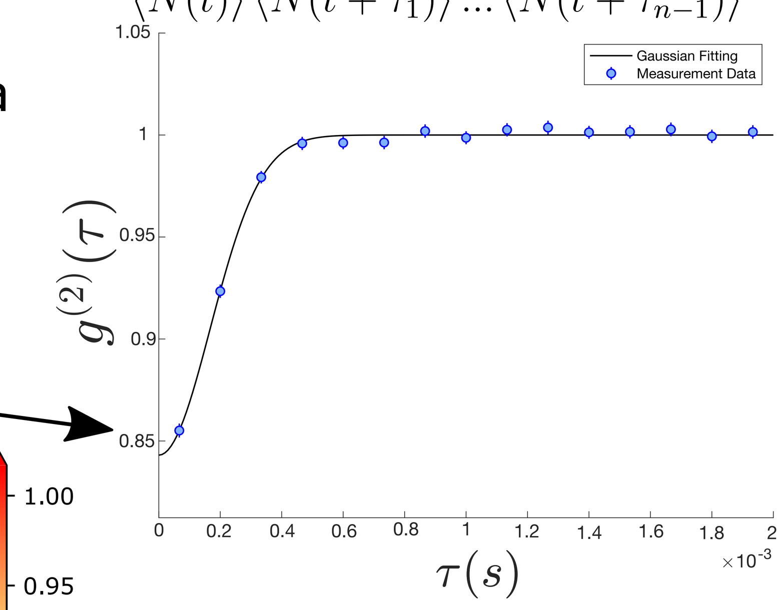
Information about manybody wavefunction is encoded in the second order correlation function

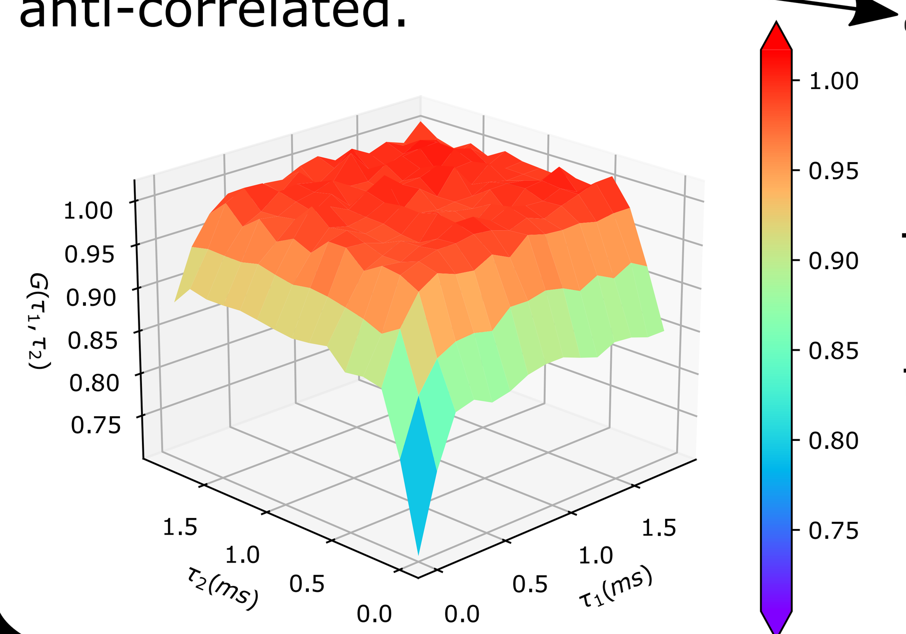
$$g^{(2)}(\tau) = \frac{\langle N(t)\times N(t+\tau)\rangle}{\langle N(t)\rangle\,\langle N(t+\tau)\rangle}$$ averaged over all *t*

and more generally $g^{(n)}(\tau_1,\ldots,\tau_{n-1}) = \frac{\langle N(t)\times N(t+\tau_1)\times\ldots\times N(t+\tau_{n-1})\rangle}{\langle N(t)\rangle\,\langle N(t+\tau_1)\rangle\ldots\langle N(t+\tau_{n-1})\rangle}$

Bosons bunch and thus have a $g^{(2)}$ peak above 1

Fermions anti-bunch and thus have a $g^{(2)}$ peak below 1, i.e. anti-correlated.





This behaviour extends to higher order correlation functions as well