QUANTUM STATISTICS OF TWIN ATOMIC BEAMS IN MATTER-WAVE DOWN-CONVERSION

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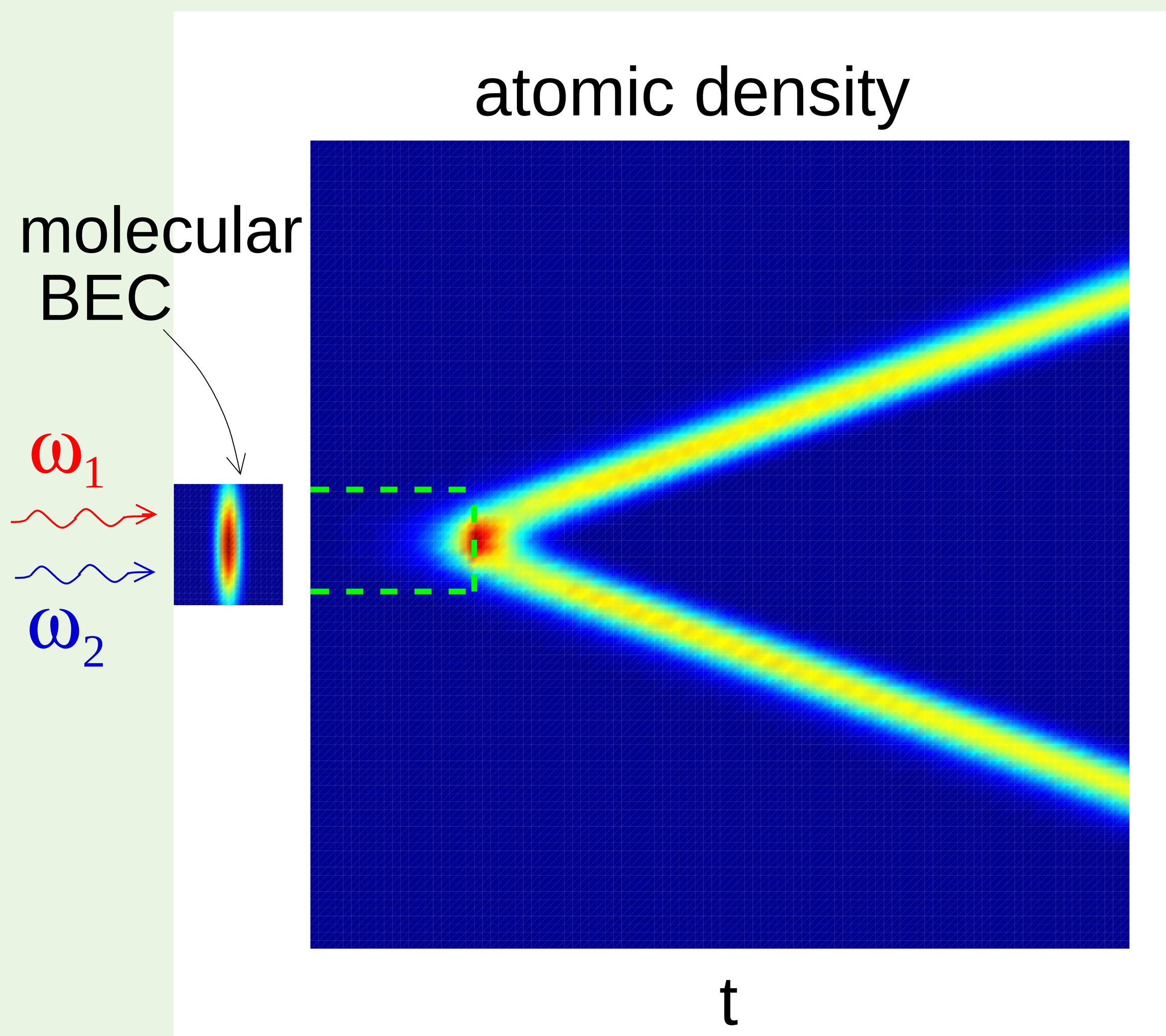
Motivation

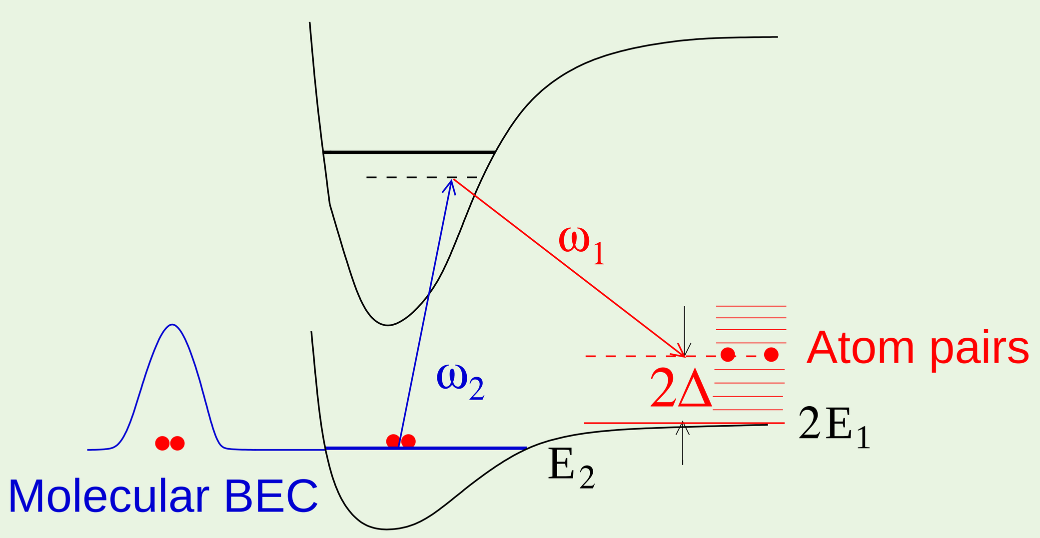
- **add parametric down-conversion of matter waves to the arsenal of nonlinear atom optics**
- possess a resource similar to production of entangled photon pairs in optical down conver-sionin

Quantum effects expected:

- strong particle number-difference squeezing in the twin atomic beam output
- EPR correlations and Bell inequalities with **massive** particles

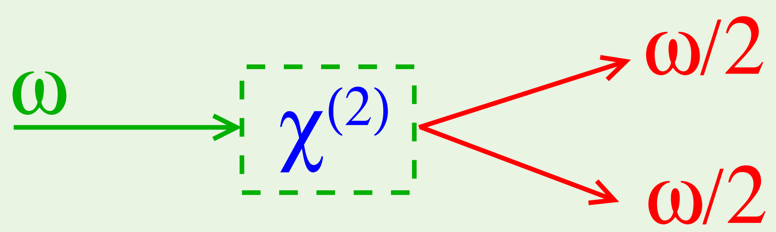
Dissociation of a molecular BEC





- Start with a BEC of molecular dimers
- **coherently** photo-dissociate the molecules into atom pairs, using Raman transitions (reverse to Raman photo-association: **[PRL 84, 5029(2000)]**)
- Energy conservation: $\hbar|\Delta| = \hbar^2 k^2/2m_1$
- Momentum conservation: $\pm k_0 = \sqrt{2m_1|\Delta|/\hbar}$

Similar to multimode travelling-wave parametric down-conversion in $\chi^{(2)}$-nonlinear optics



Parametric field theory (1D)

$$H_0 = \sum \int dx \left[\frac{\hbar^2}{2m_i} |\nabla \hat{\Psi}_i|^2 + \hbar\Delta \hat{\Psi}_1^\dagger \hat{\Psi}_1 + V_2 \hat{\Psi}_2^\dagger \hat{\Psi}_2 \right]$$
$$H_{int} = \frac{\hbar\chi}{2} \int dx \left[\hat{\Psi}_2 \hat{\Psi}_1^\dagger \hat{\Psi}_1^\dagger + H.c. \right]$$
$$H_{self} = \sum \frac{\hbar U_{ij}}{2} \int dx \hat{\Psi}_i^\dagger \hat{\Psi}_j^\dagger \hat{\Psi}_j \hat{\Psi}_i$$

- $\hat{\Psi}_{1/2}(t,x)$ – atomic/molecular field operators
- χ – atom-molecule conversion rate
- $U_{11} = 4\pi\hbar a_{11}/m_1$ – s-wave scattering
- $2\Delta = (2E_1 - E_2)/\hbar - (\omega_2 - \omega_1)$ – two-photon detuning (like phase mismatch in optics)
- include losses

Approximations

- **neglect molecular field depletion**: replace $\hat{\Psi}_2$ by c-number; assume a Thomas-Fermi profile for the molecular BEC density n_2:

$$\chi(t)\hat{\Psi}_2(x) \rightarrow \chi(t)\sqrt{n_2(x)} \equiv \tilde{\chi}(t,x)$$
$$\Delta + U_{12}\hat{\Psi}_2^\dagger(x)\hat{\Psi}_2(x) \rightarrow \Delta + U_{12}n_2(x) \equiv \tilde{\Delta}(x)$$

- limit to short interaction times and small number of atoms produced, and neglect atom-atom s-wave scattering

Techniques

Solve numerically the positive-P stochastic differential equations with noise terms (all quantum effects are retained and treated exactly)

Relative number squeezing

- Quantum correlations:

$$V = \langle [\Delta(\hat{N}_- - \hat{N}_+)]^2 \rangle \Big/ (\langle \hat{N}_- \rangle + \langle \hat{N}_+ \rangle)$$
$$= 1 + [\langle : (\hat{N}_+)^2 : \rangle - \langle \hat{N}_- \hat{N}_+ \rangle] \Big/ \langle \hat{N}_+ \rangle$$

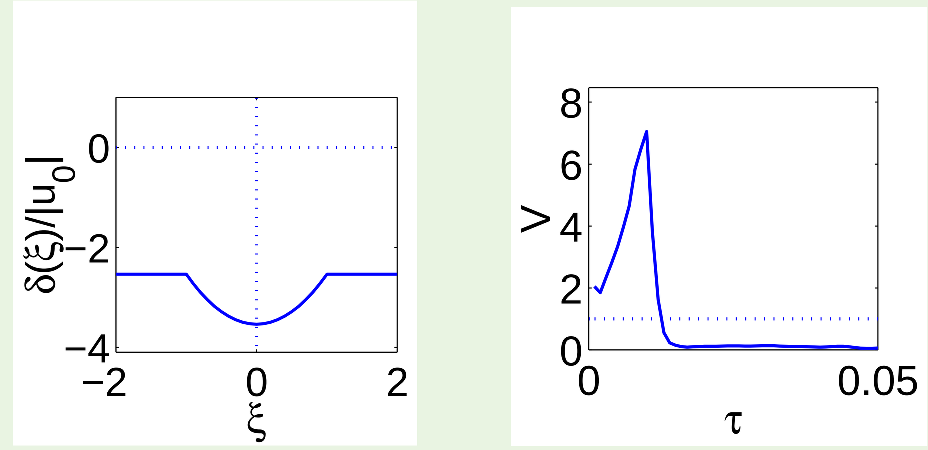
– normalized variance of fluctuations in the particle number difference (with $\Delta\hat{X} \equiv \hat{X} - \langle \hat{X} \rangle$), where $\hat{N}_{+(-)}(t) = \int_{0(-\infty)}^{+\infty(0)} dx \hat{\Psi}_1^\dagger(x)\hat{\Psi}_1(x)$

- **squeezing** corresponds to: $V < 1$
- **Twin beams = spatial separation AND squeezing**

Example of twin atomic beams

– see figure on the left –

To allow the atoms to escape the effective trap due to atom-molecule interactions (U_{12}), $\tilde{\Delta}(x) = \Delta + U_{12}n_2(x)$, need: $|\Delta| \gg |U_{12}|n_2(0)$

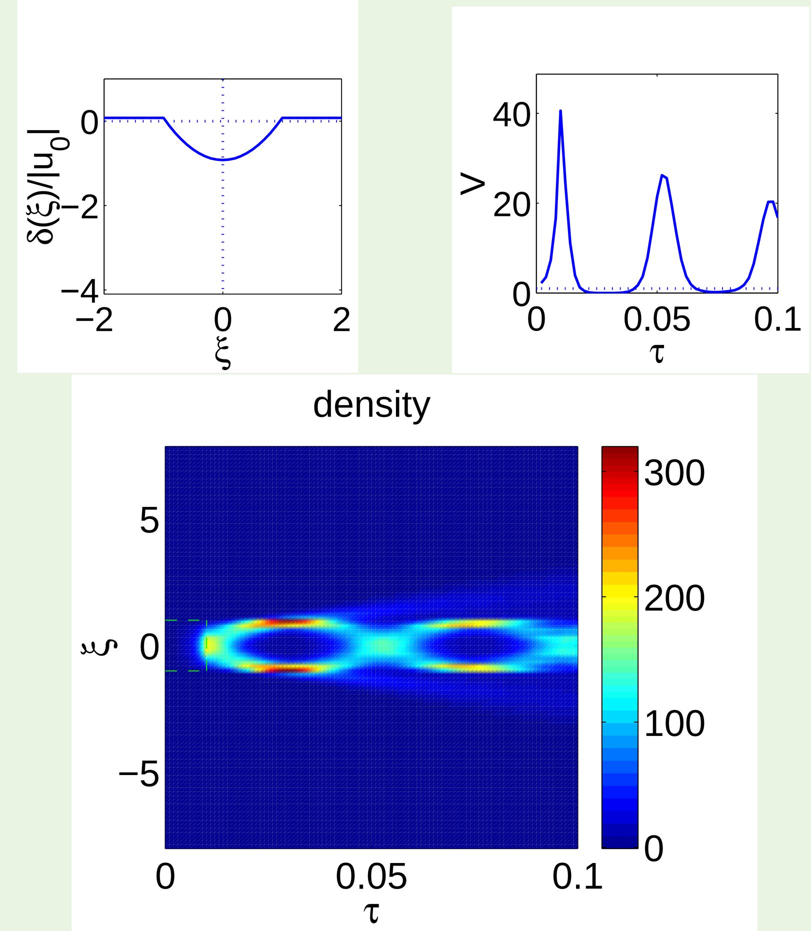


Characteristic parameter values

- $a_{22} \simeq a_{11} = 5.4$ nm, $a_{12} = -9.25$ nm (^{87}Rb)
- $\Delta = -2 \times 10^4$ s^{-1}
- molecular BEC: $60\mu m$; aspect ratio: 100
- initial number of molecules: 1.5×10^3
- final number of atoms: 100; losses: 10%
- dissociation time: 27 ms
- **squeezing: 93% ($V = 0.07$)**

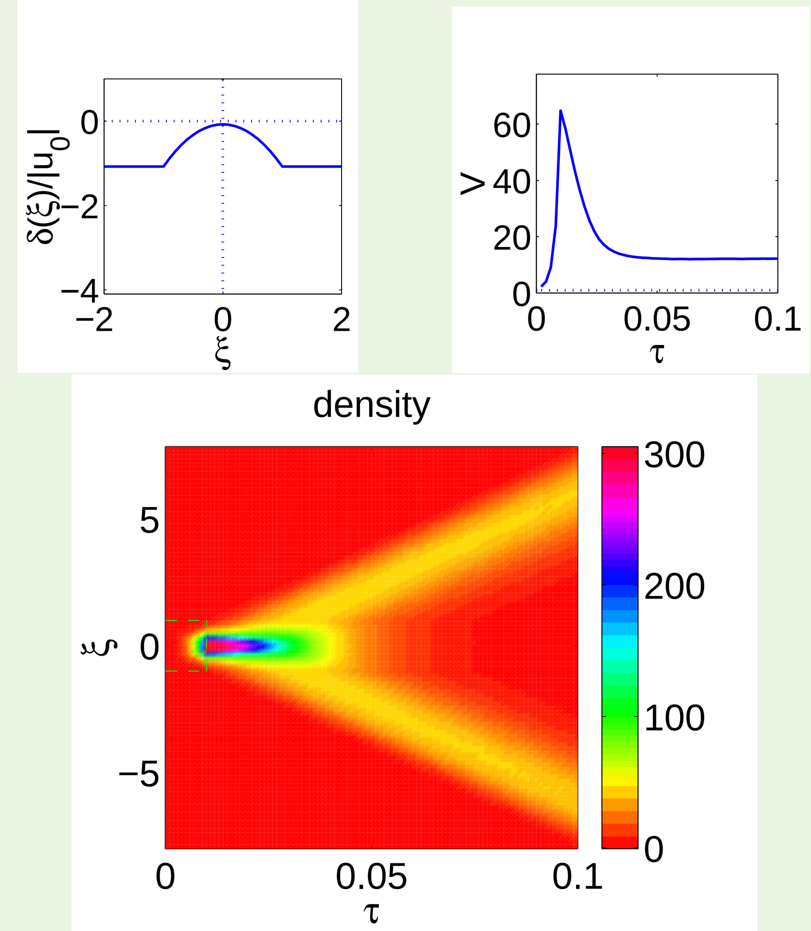
Example of trapped beams

Strong attractive atom-molecule S-wave scattering: $U_{12}n_2(x)$ acts like a trapping potential



Two beams, NOT twins ($V > 1$)

Strong repulsive atom-molecule S-wave scattering: $U_{12}n_2(x)$ acts like a potential barrier.



Summary

- scheme for generating strongly correlated twin atom-laser beams
- phase insensitive and robust against losses
- measurement of the particle number in one of the beams would produce a single beam with well-defined particle number

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