Bragg pulses shaping in an atomic interferometer

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Principle of a Bell test with momentum-entangled atoms

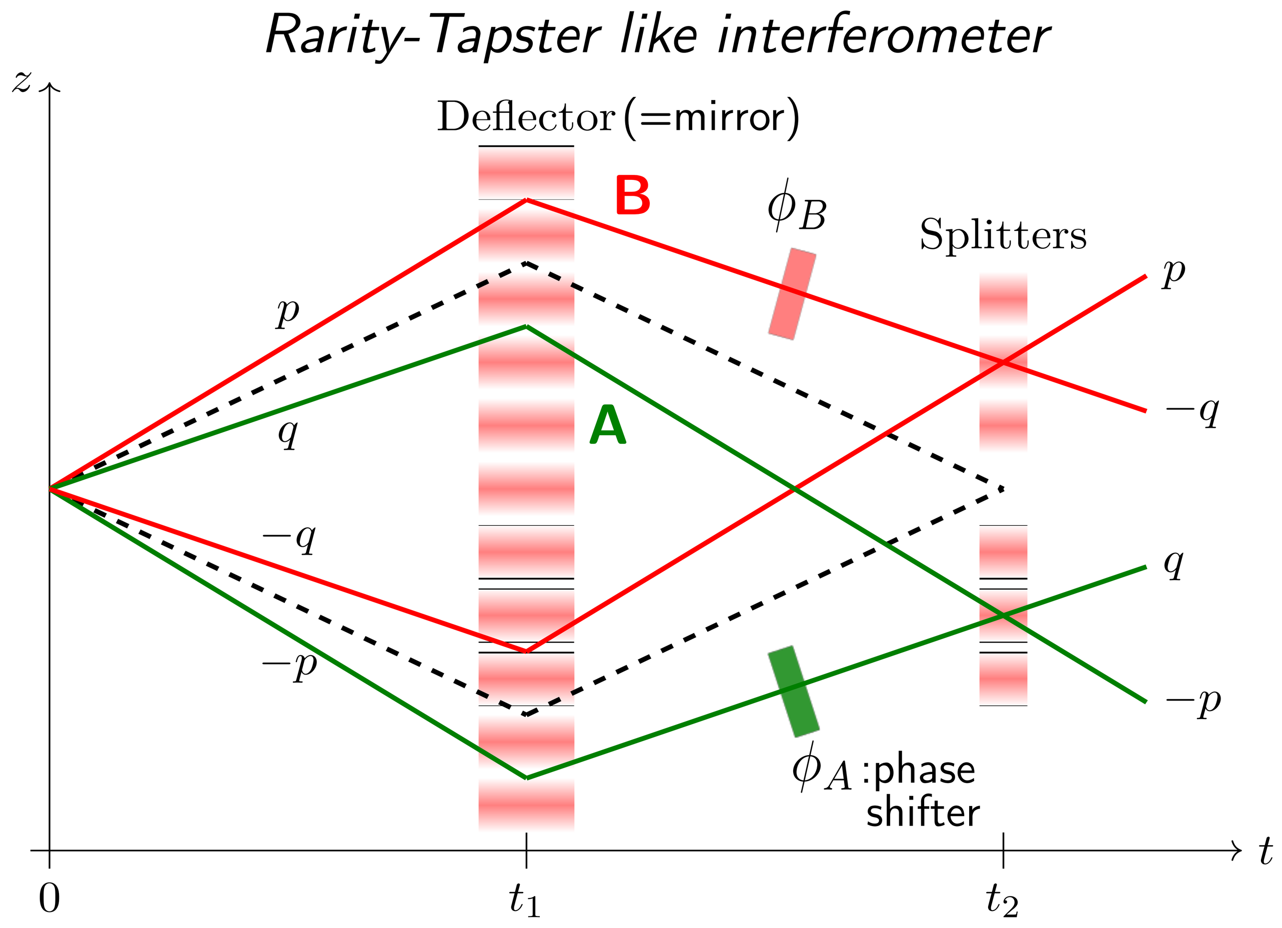
Goal: Performing a Bell inequality test with massive particles and external degrees of freedom entanglement

Source of entangled pairs of atoms:
- BEC of metastable helium in a dipole trap
- pair creation lattice (four-wave mixing process)

Bonneau *et al.*, *PRA* **87**, 061603(R) (2013)

$$|\psi_{\rm in}\rangle = \frac{1}{\sqrt{2}}(|p,-p\rangle + |q,-q\rangle)$$

Rarity-Tapster like interferometer

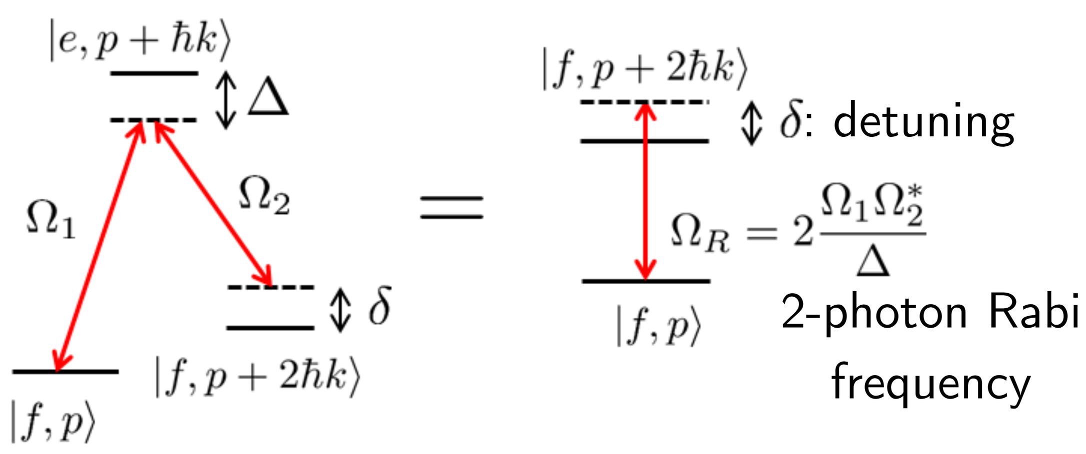


Rarity & Tapster, *PRL* **64**, 2495 (1990)
Dussarrat *et al.*, *PRL* **119**, 173202 (2017)

Deflectors and 50/50 splitters: Bragg beams

A two-photons transition between two momentum states

$|q\rangle \longleftrightarrow |-p\rangle$: interferometer **A**
$|p\rangle \longleftrightarrow |-q\rangle$: interferometer **B**



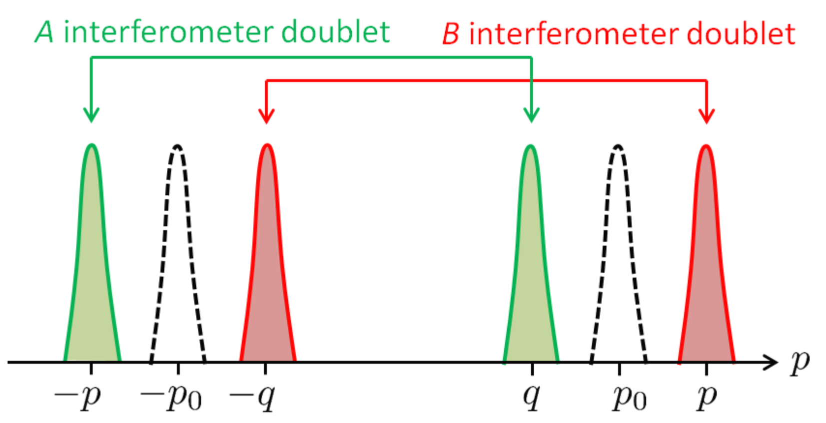
Detector: MicroChannel Plate
- 3D momentum distribution after time of flight $\rightarrow$ joint probabilities of detection $\mathcal{P}(p,q)$
- Single atom detection: expected efficiency ~40%

Bell: Correlator: $E = \mathcal{P}(p,q) + \mathcal{P}(-p,-q) - \mathcal{P}(p,-q) - \mathcal{P}(q,-p)$

Quantum theory predicts that the Bell correlator oscillates as a function of the phase difference between A and B : $E = \cos(\phi_A - \phi_B)$

Bell parameter: $S(\phi_A, \phi'_A, \phi_B, \phi'_B) = E(\phi_A, \phi_B) - E(\phi_A, \phi_B) + E(\phi'_A, \phi_B) + E(\phi'_A, \phi'_B)$; classical $S \leq 2$; quantum $S > 2$ possible

Bragg coupling: two-level model



The A doublet and the B doublet do not have the same Bragg transition resonance frequency

The Bragg interaction is modeled by a two-level system:

$$|\psi(t)\rangle = C_0(t)\, e^{-iE_0 t/\hbar}\,|p\rangle + C_2(t)\, e^{-iE_2 t/\hbar}\,|p+2\hbar k\rangle \quad \text{for a given doublet}$$

The dynamics is given by:

$$\begin{pmatrix} \dot{C}_0(t) \\ \dot{C}_2(t) \end{pmatrix} = i \begin{pmatrix} 0 & \frac{\Omega_R(t)}{2} e^{i\delta t} \\ \frac{\Omega_R^*(t)}{2} e^{-i\delta t} & 0 \end{pmatrix} \begin{pmatrix} C_0(t) \\ C_2(t) \end{pmatrix}$$

We study each pulse (deflector and splitter) separately, starting with: $C_0(0) = 1$, $C_2(0) = 0$

Bragg pulses shaping

$$\begin{cases} C_0(0) = 1 \\ C_2(0) = 0 \end{cases} \xrightarrow[\Omega_R(t)]{\text{Bragg}} \begin{cases} C_0(T) = \sqrt{T} e^{i\phi_t} \\ C_2(T) = \sqrt{R} e^{i\phi_r} \end{cases}$$

R: reflectivity
T: transmittivity

Dephasing: $\Phi = \phi_t - \phi_r$

Criteria
- Deflector: $R(\delta) \approx 1$ over a large range of δ (for multiplexing)
- Splitter: $R(\delta) \approx 0.5$ over a large range of δ
  + independant phase control for A and B ($\Phi_A \neq \Phi_B$)

Optimization principle

Perturbative approximation

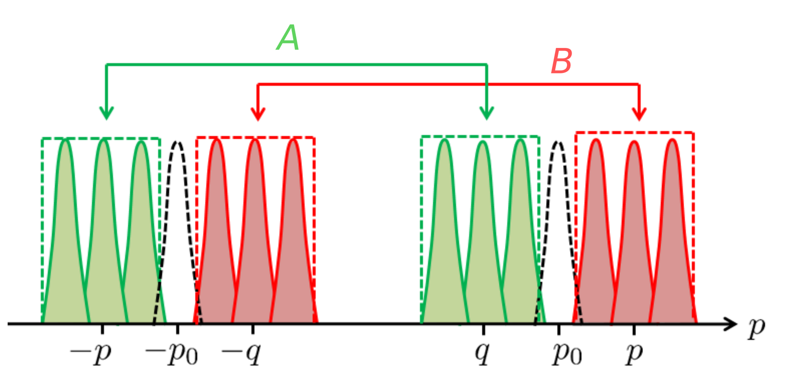
$C_2(T) \approx \frac{i}{2} \text{FT}\,[\Omega_R^*(t)]\,\{\delta\}$ $\rightarrow$ we start with sinc temporal pulses in order to have a flat profile of R in δ

Fang *et al.*, *NJP* **20**, 1367 (2018)

Splitter

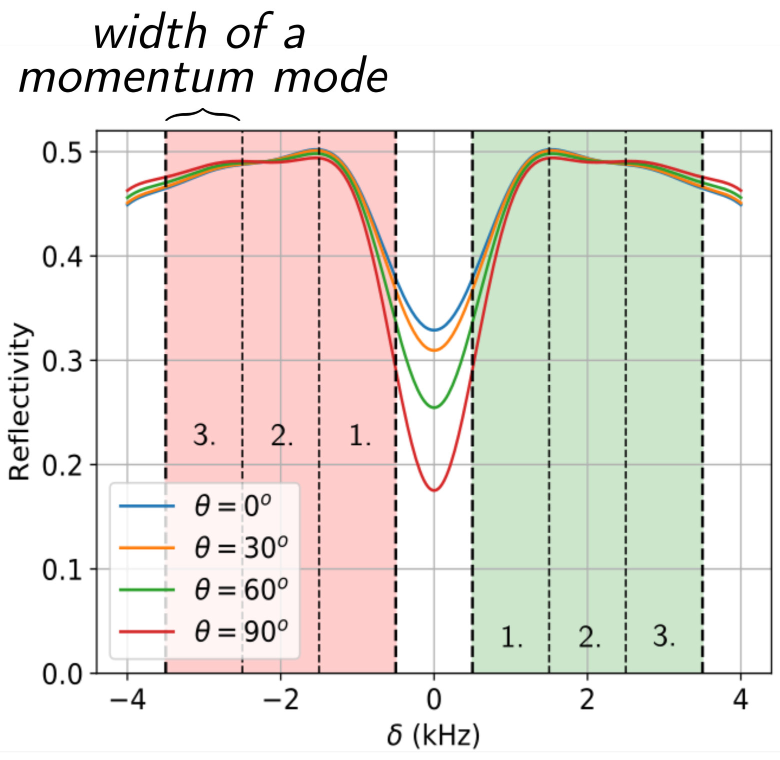
Goal: independant control of A & B

Idea: Sending a two-frequencies pulse with different phases, adressing the two doublets

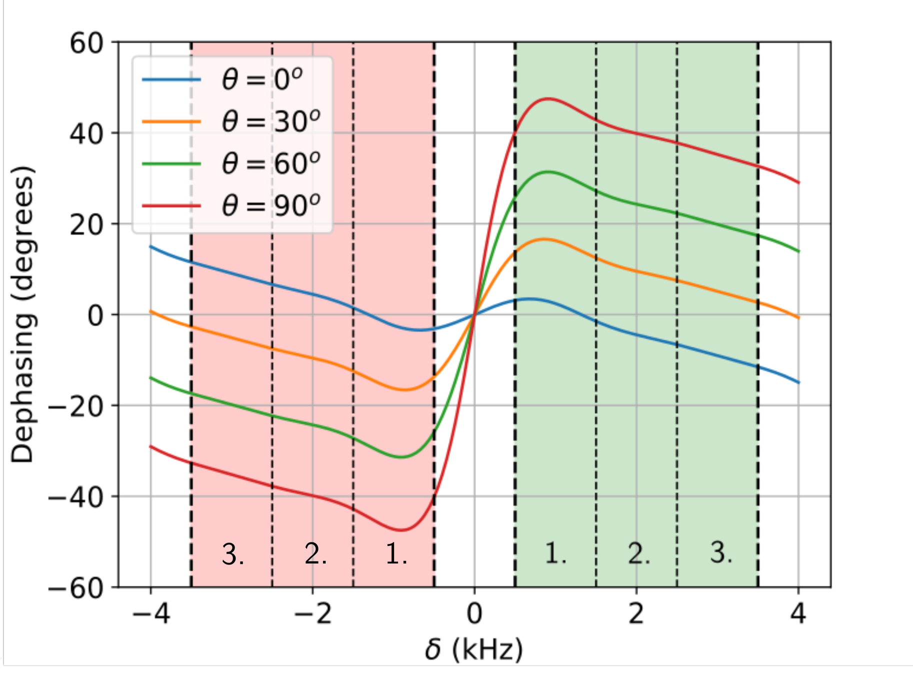


$$\Omega_R(t) = \Omega_M\, \text{sinc}(\Omega_S(t - T/2)) \times \left(e^{\frac{i\Omega_D(t-T/2)}{2}} + e^{\frac{-i\Omega_D(t-T/2)}{2} + i\theta}\right)$$

resonant with A — resonant with B — controllable phase



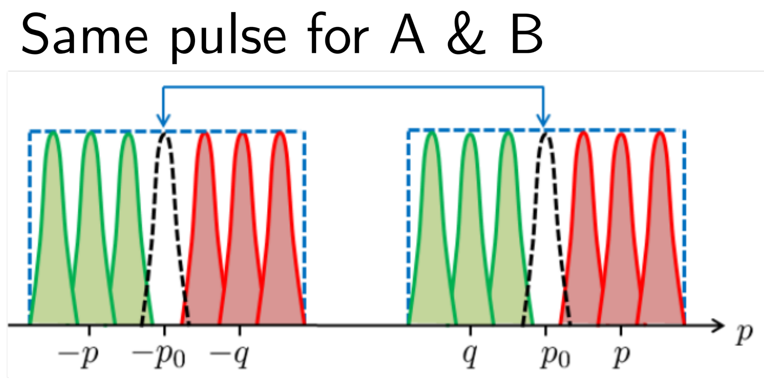
$\Longrightarrow$ good reflectivity



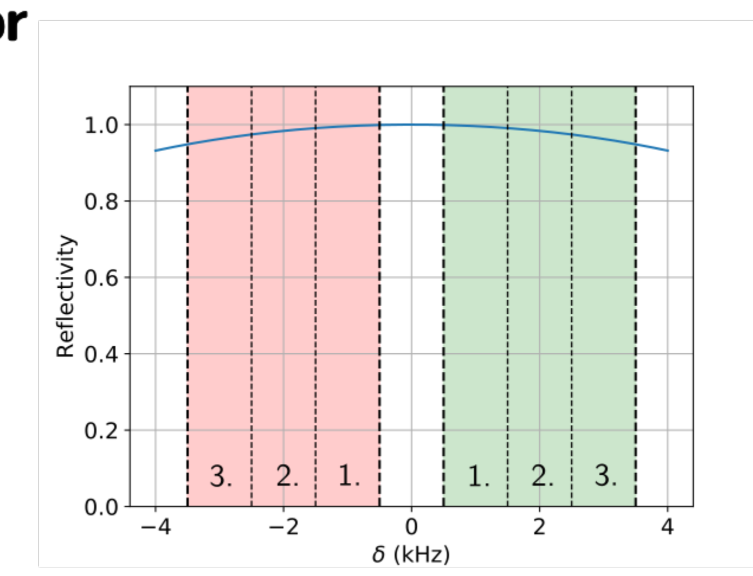
$\Longrightarrow$ dephasing controlled by θ

Deflector

Same pulse for A & B



$$\Omega_R(t) = \Omega_M\, \text{sinc}(\Omega_S(t - T/2))$$



$\Longrightarrow$ good reflectivity

Bell correlator calculation

$$E(\delta) = A(\delta)\, \cos(\theta + \Phi(\delta))$$

$\rightarrow$ phase control ✓
$\rightarrow$ good reflectivity ✓
$\Longrightarrow$ good amplitude

We should be able to measure the violation of Bell inequality predicted by quantum theory