The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2030-28

Conference on Research Frontiers in Ultra-Cold Atoms

4 - 8 May 2009

Generation of a synthetic vector potential in ultracold neutral Rubidium

SPIELMAN Ian

National Institute of Standards and Technology
Laser Cooling and Trapping Group
100 Bureau Drive
Gaithersburg MD 20899-8424
U.S.A.

Generation of a synthetic vector potential and an *E* field

I. B. Spielman

Team
Y.-J. Lin, R. L. Compton, A. R. Perry, and K. Jimenez-Garcia

Senior coworkers
J. V. Porto, and W. D. Phillips

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

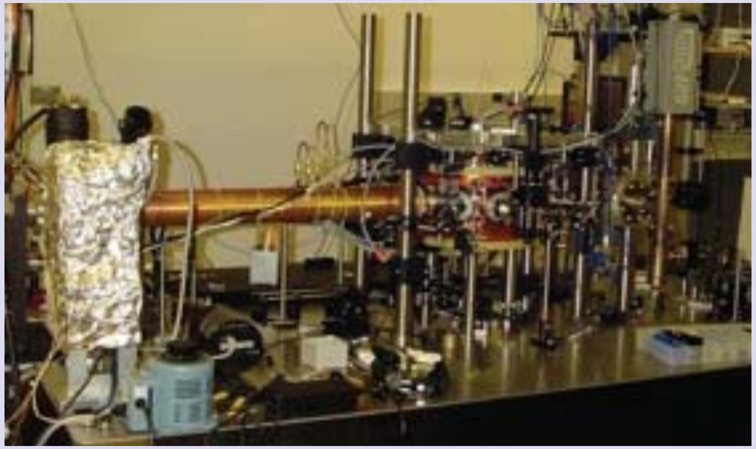
Funded by the DARPA OLE program, ONR, and
the NSF through the PFC at JQI.

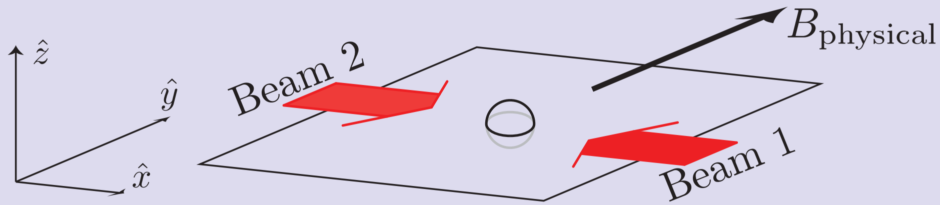
May, 2009

Outline for today

Raman dressed states

Brief description of theory and implementation

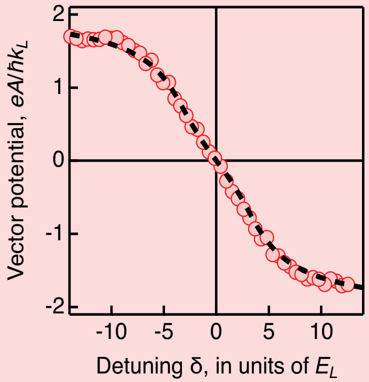




A synthetic vector potential

Experimentally verify a vector potential appears

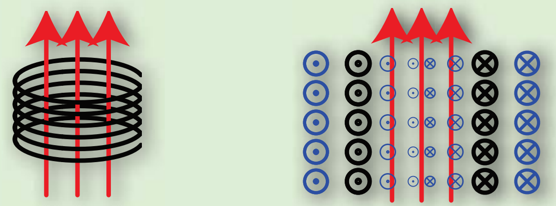
$$\hat{H} = \frac{1}{2m}\left[\left(\hat{p}_y + q\hat{A}_y\right)^2 + \left(\hat{p}_x + q\hat{A}_x\right)^2\right] + V(\hat{x})$$



An electric field appears

Temporal variation of A gives rise to an electric field.

$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t}$$



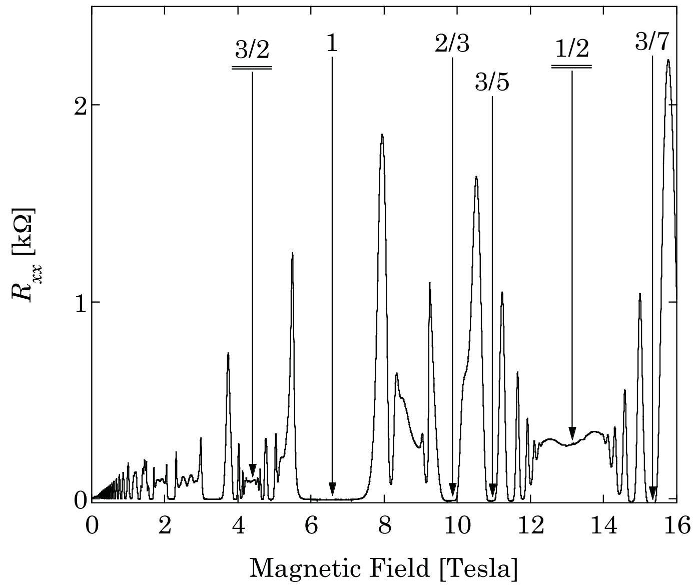
Motivation

Fundamental physics

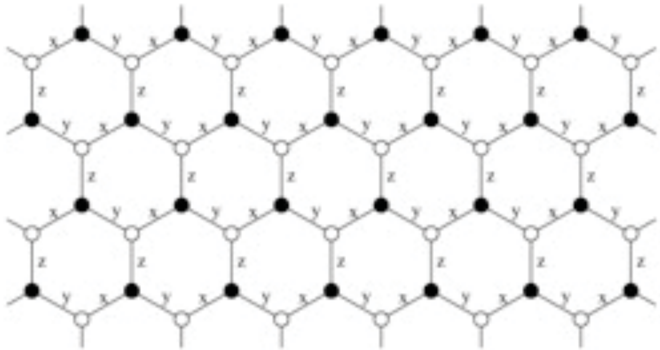
Under what general conditions can physical systems support excitations with quantum numbers and statistical angles which are not simple multiples of the constitute particles?

E.g., quantum Hall systems, quantum magnets, *p*-wave superconductivity, ...
(all can potentially be studied in cold atom systems)

FQHE Systems



Spin 1/2 system: Kitaev lattice



Refs.

[1] R. B. Laughlin. PRL **50** p1395 (1983).
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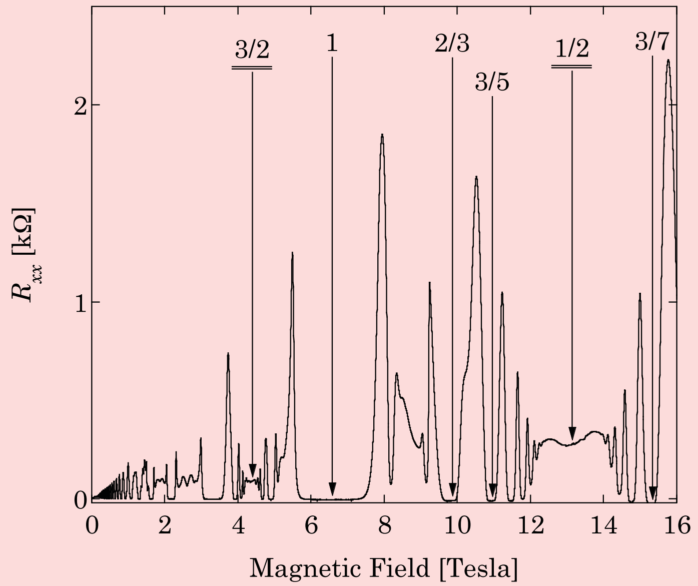

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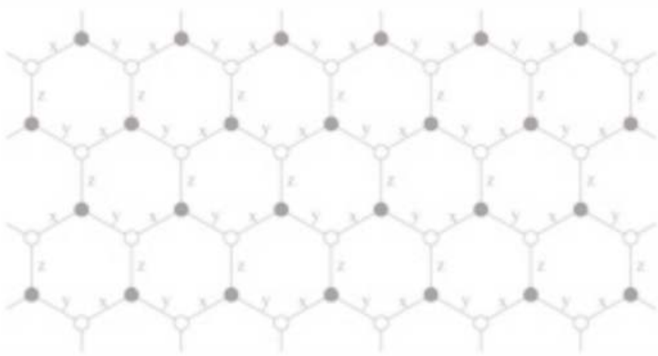

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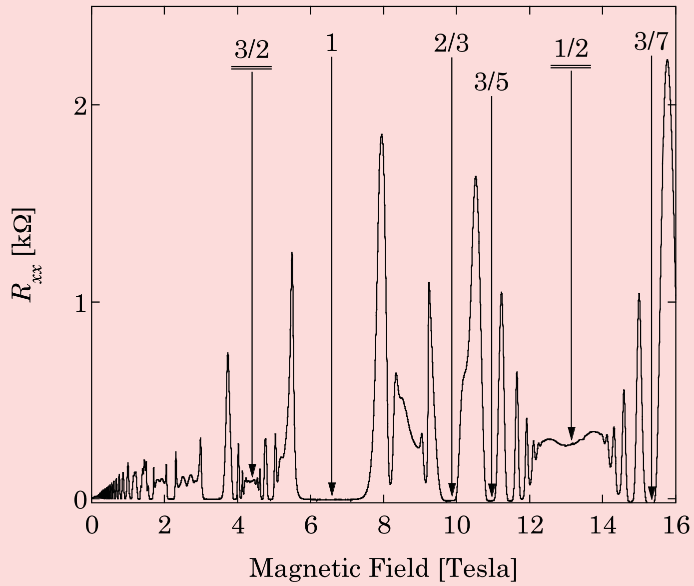
Motivation: magnetic fields

FQHE Systems



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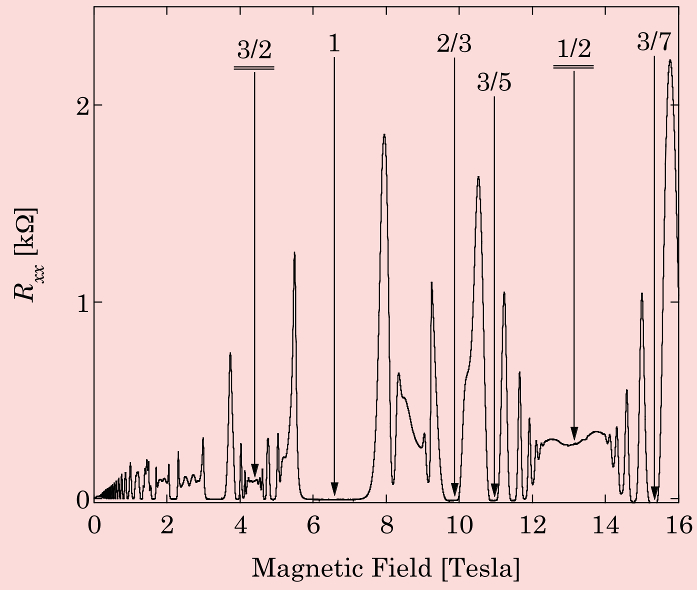
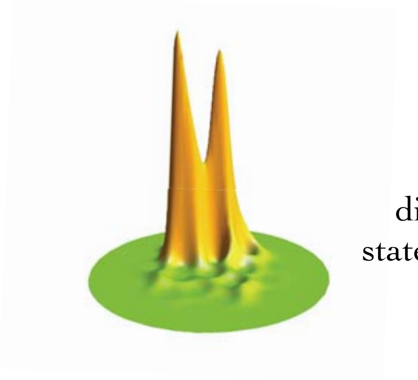


Bosons at high field

At filling factor 1/2 the Laughlin state is the *exact* ground state.

Binary contact interactions *are* sufficient to generate some non-abelian states (Moore-Read), but not all (Read-Rezayi).



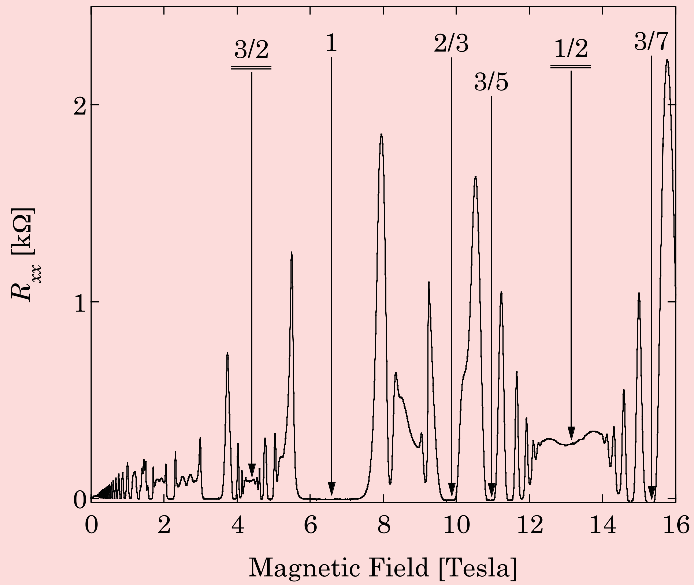
Single atom probability distribution in Laughlin 1/2 state, fixing coordinates of other atoms.

Reference

N. R. Cooper Advances in Physics 57, 539 (2008)

How to “charge” neutral particles

FQHE Systems



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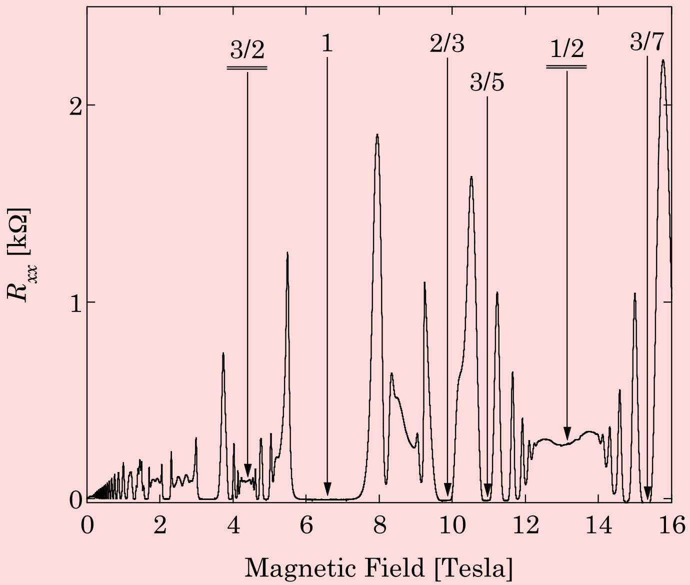
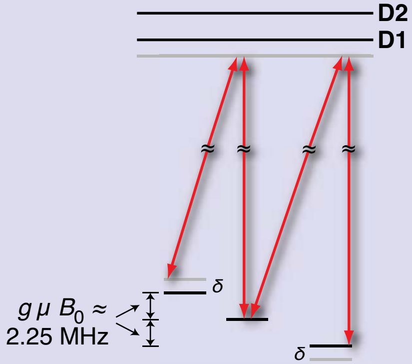




How to simulate magnetic fields

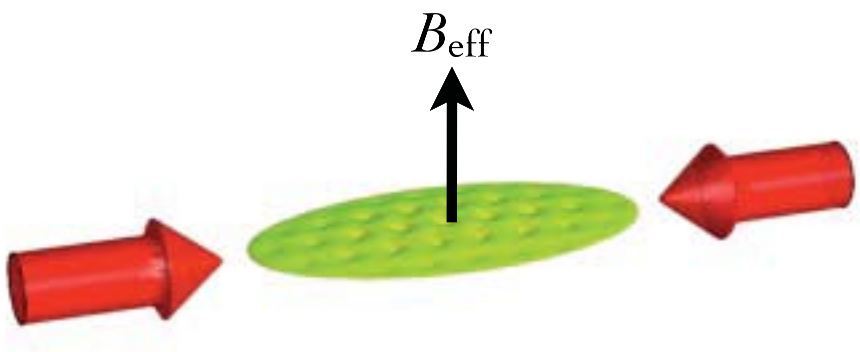
(1) Rotation: the Hamiltonian in the rotating frame has an effective field. To reach high fields fine tuning is required to compensate the centripetal term: small numbers.

(2) Stroboscopic proposal: precise modulation of lattices and background potentials.

References: V. Schweikhard et al PRL **92** p040404 (2004),
A. Sørensen, et al PRL **94** p086803 (2005),

Our approach

(3) Raman techniques.



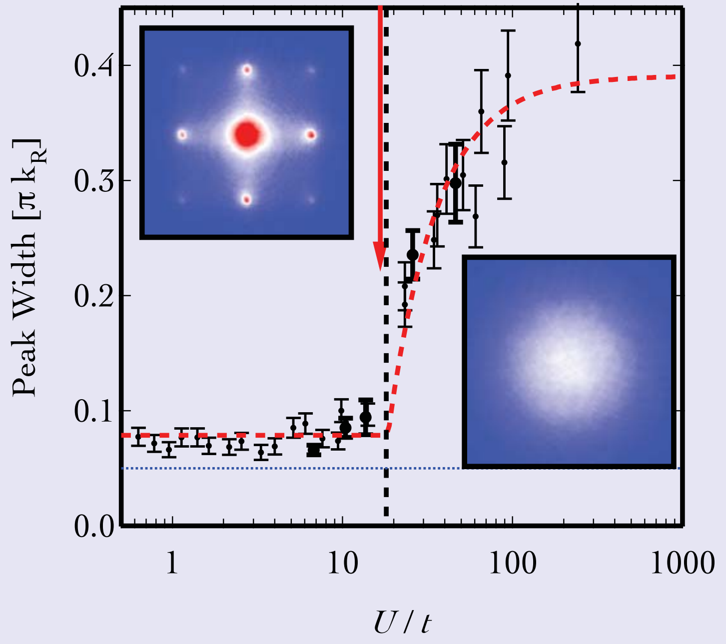
Reference: G. Juzeliñuas et al PRA ***73*** p025602 (2006)

Cold atoms: a platform for many-body physics

We can control the hamiltonian for cold atoms in a number of ways.

$$\hat{H} = \sum_j \left[\frac{\hat{p}_j^2}{2m} + V(x_j) \right] + \sum_{i<j} U(x_i - x_j)$$

Potential: optical and magnetic forces.
Lattice physics, 2D SF to MI transition



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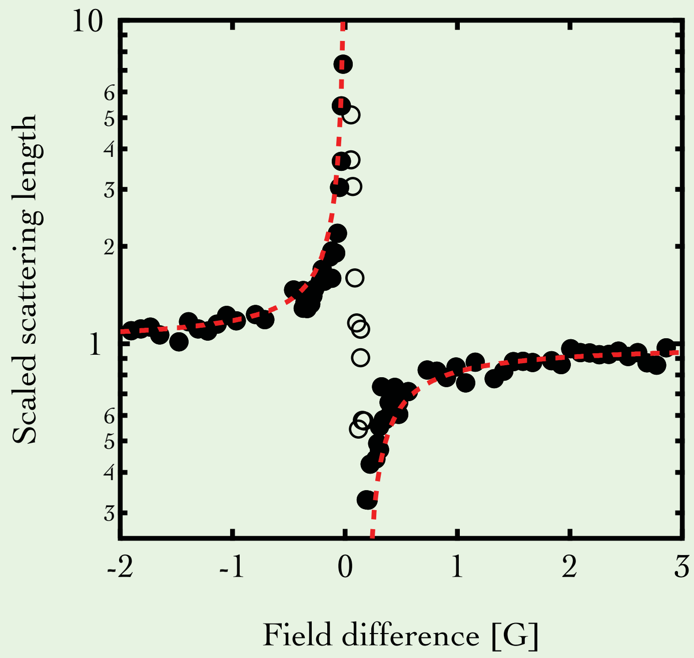
Interaction: Choice of atom and collisional Feshbach resonances.
Careful observation of ^{87}Rb resonance



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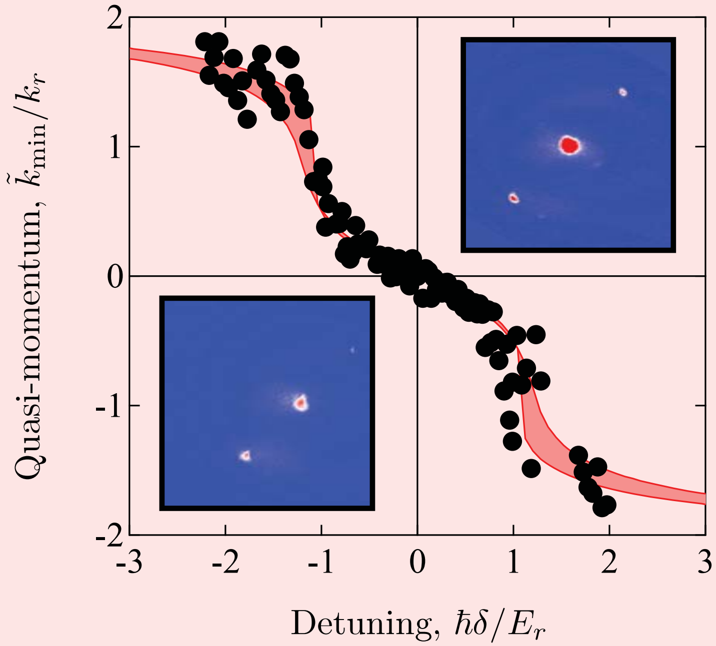
Careful observation of ^{87}Rb resonance

Kinetic: We have been working to control the kinetic energy term.
Synthetic vector potentials



Experimental control of cold atoms systems

We can control the hamiltonian for cold atoms in a number of ways.

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We have been working on producing the same level of control with the *kinetic* energy term.

Here I will be interested in a synthetic field in the 2D plane.
Some common gauge choices are:

$$A = \left\{ -\frac{By}{2}, \frac{Bx}{2}, 0 \right\}$$

Symmetric gauge: natural for rotating systems

$$A = \{0, Bx, 0\}$$

Landau gauge: relevant here

Expect the usual relations for fields

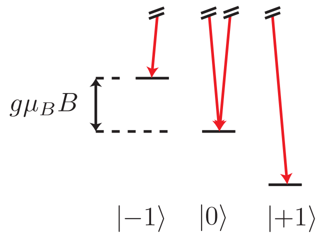
$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} \qquad B = \nabla \times A$$

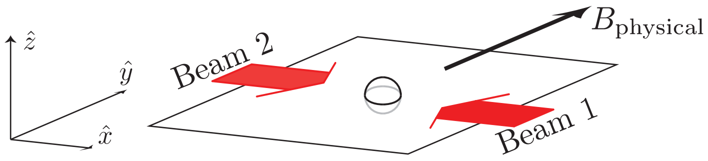
References
J. C. Maxwell (1873)

Atom light interaction

Atom light interaction

Given the following geometry and levels





Coupled Hamiltonian

We will want to label states, so I will start with the expected:

$$|k, \sigma\rangle$$

Absent the lasers the 1D Hamiltonian for motion along x is

$$H_0 = \sum_k \left(\frac{\hbar^2 k^2}{2m} - \frac{\delta}{2}\right) |k,1\rangle\langle k,1| + \left(\frac{\hbar^2 k^2}{2m} + \frac{\delta}{2}\right) |k,2\rangle\langle k,2|$$

The Raman beams couple states via

$$H_{\text{int}} = \sum_k \left(\frac{\Omega}{2}|k - 2k_r, 2\rangle\langle k,1| + \frac{\Omega}{2}|k,1\rangle\langle k - 2k_r, 2|\right)$$

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Atom light interaction: pictures

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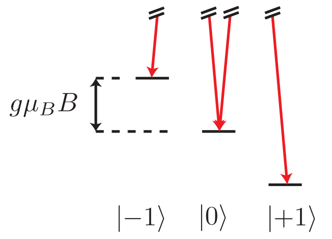
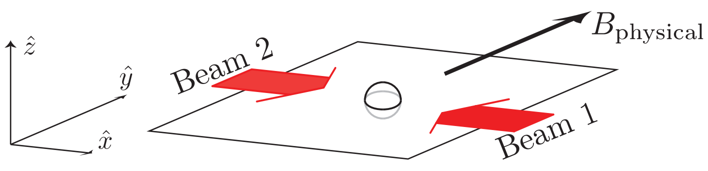
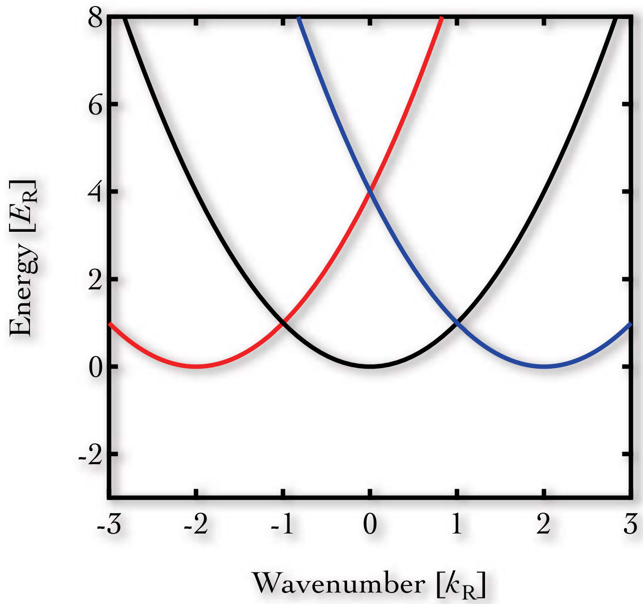




Coupled States

States will be labeled by:
(1) the "band index" and by
(2) a quasi-momentum k



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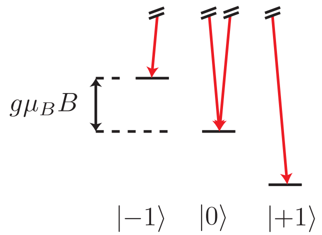

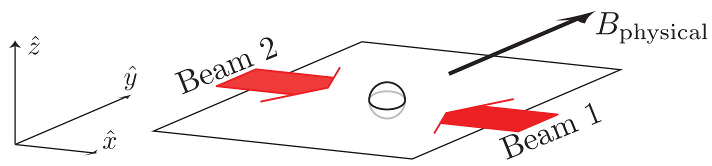

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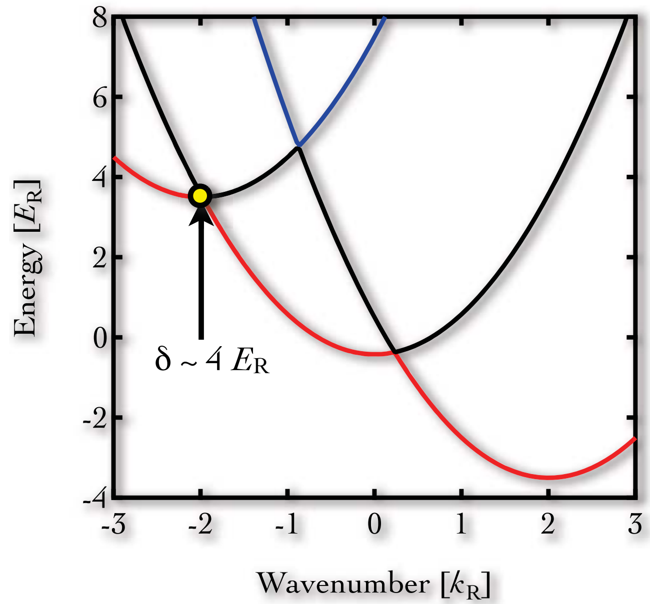

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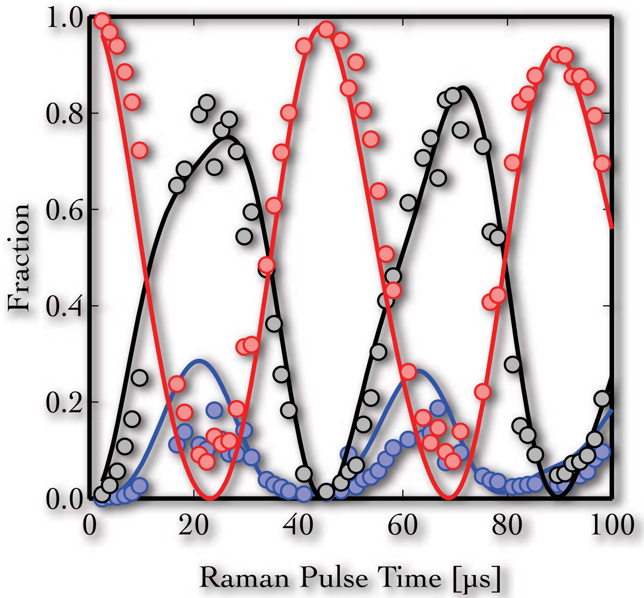
Atom light interaction: pictures

Time evolution

In the sudden limit (Raman-Nath)
Population oscillations yield coupling



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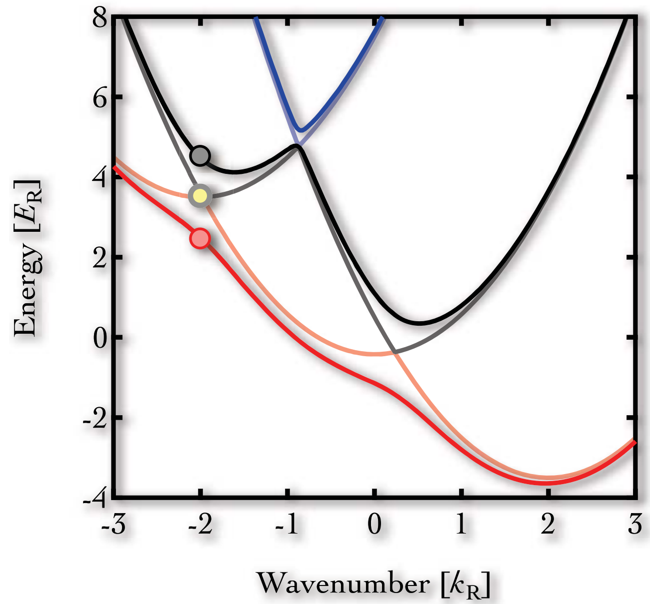

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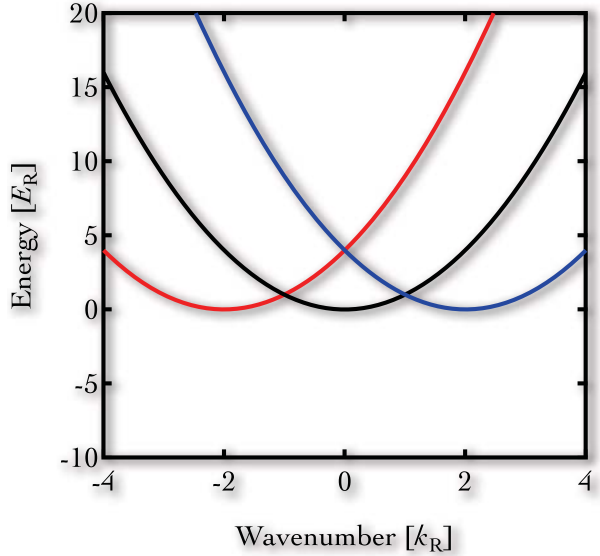
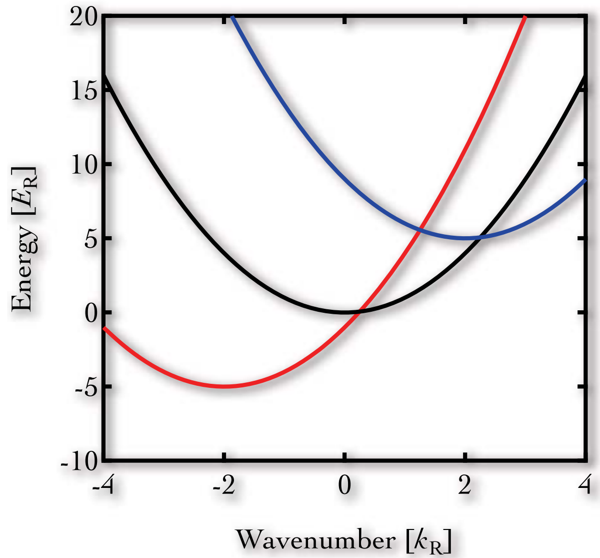
Atom light interaction: vector potential





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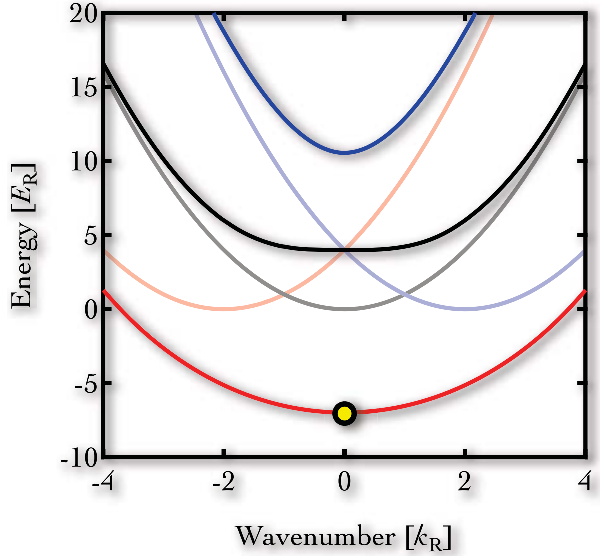
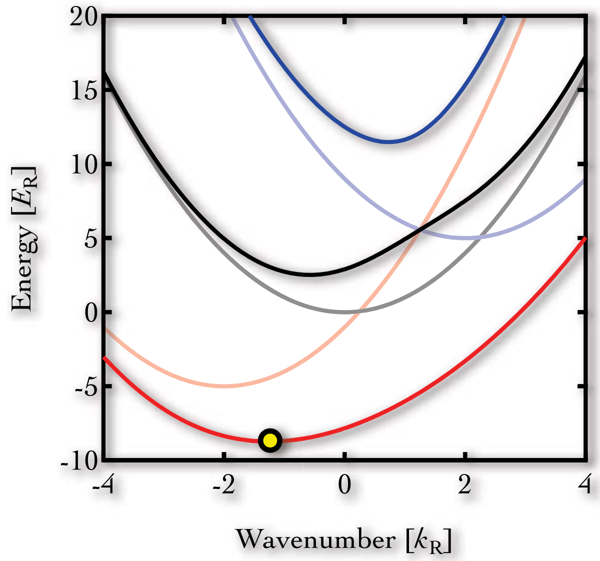
Atom light interaction: vector potential





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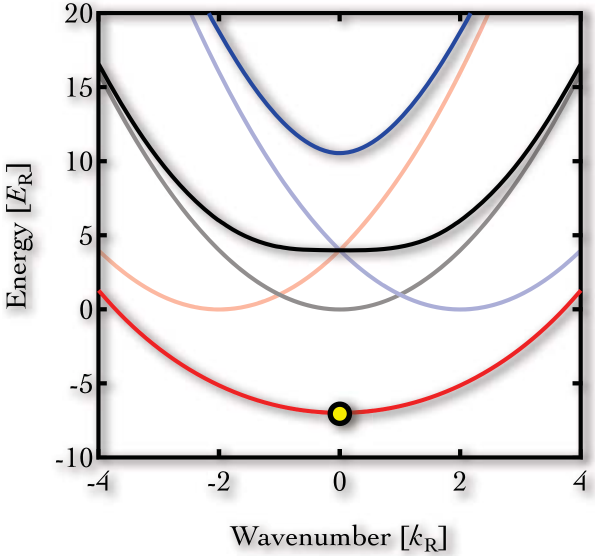
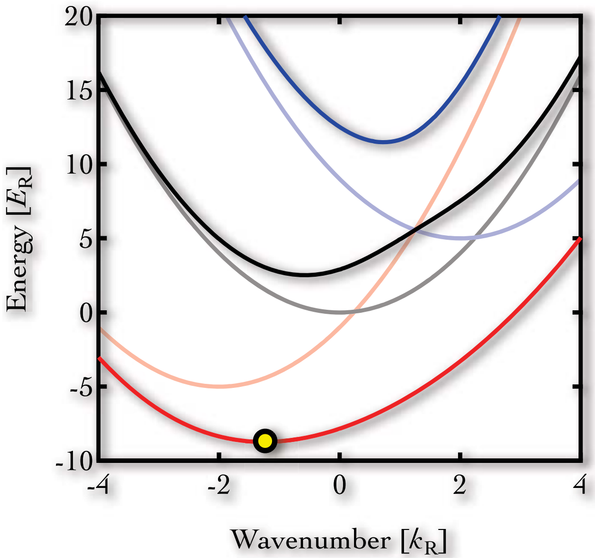
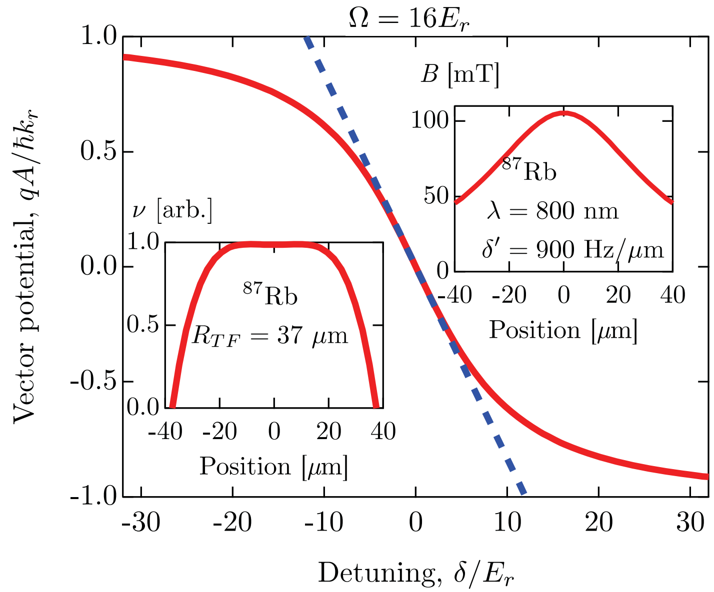




Effective vector potential



$$\frac{m^*}{m} \approx \frac{\Omega}{\Omega \pm 4}$$

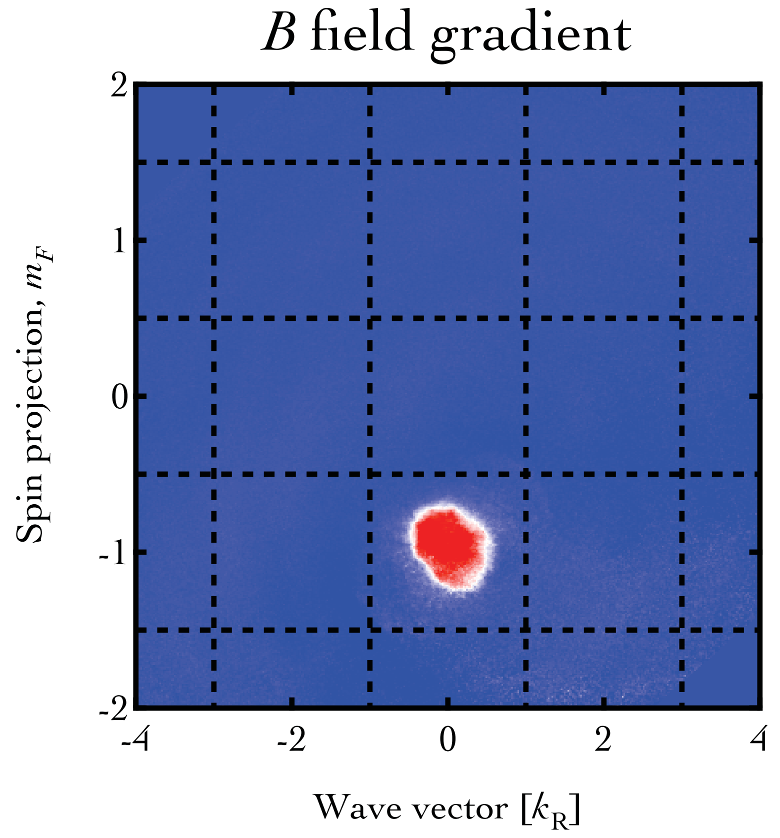
$$\frac{qA}{\hbar k_r} \approx \frac{\delta}{4 \pm \Omega}$$

$$\frac{\delta'}{E_r} \approx \frac{2 \pm \Omega}{2} + \frac{\delta^2(4 \pm \Omega)}{4(4+\Omega)^2}$$

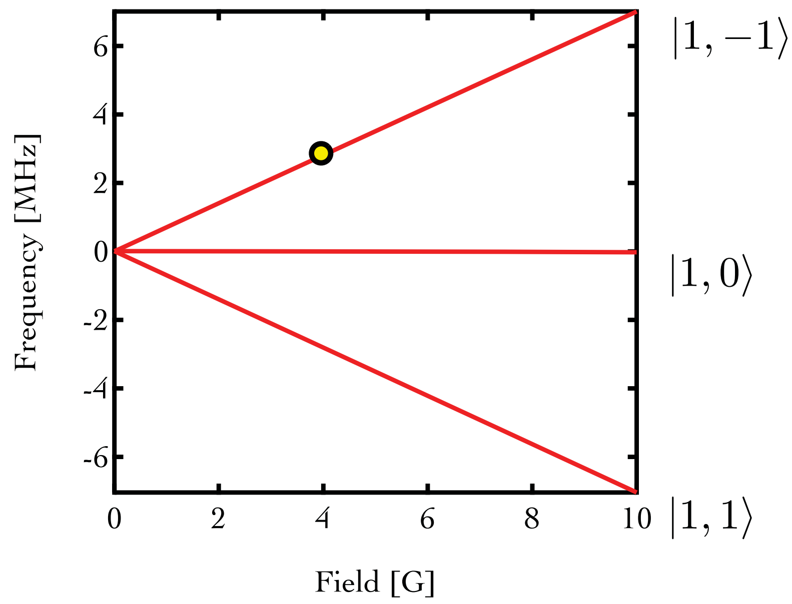
Reality check

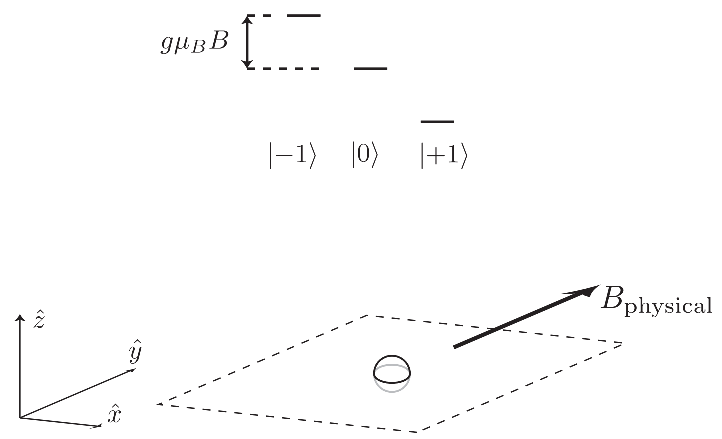
Adiabatic manipulation of atoms

Initial state $|F=1, m_F=-1\rangle$



Breit-Rabi result for ^{87}Rb





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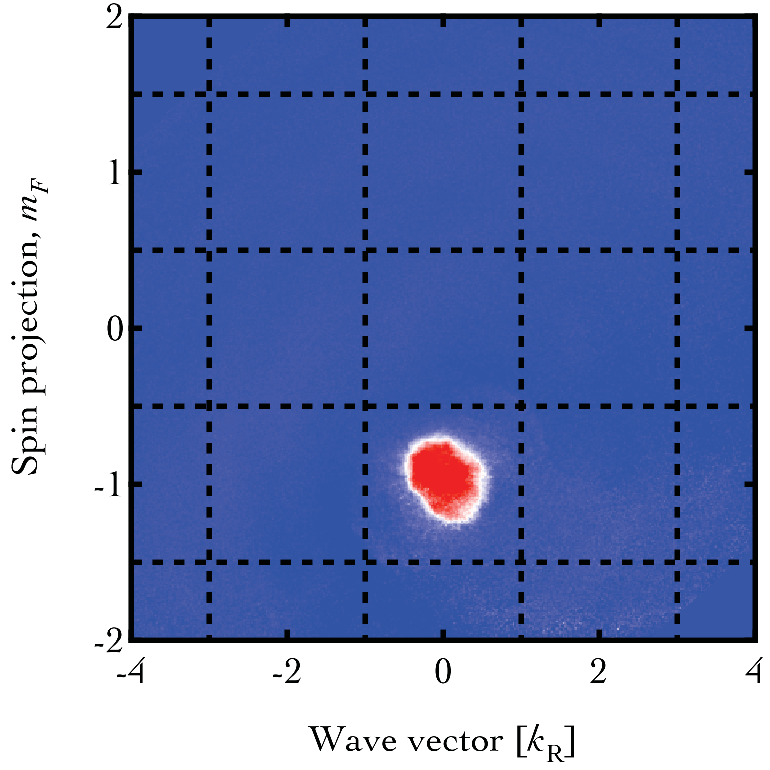

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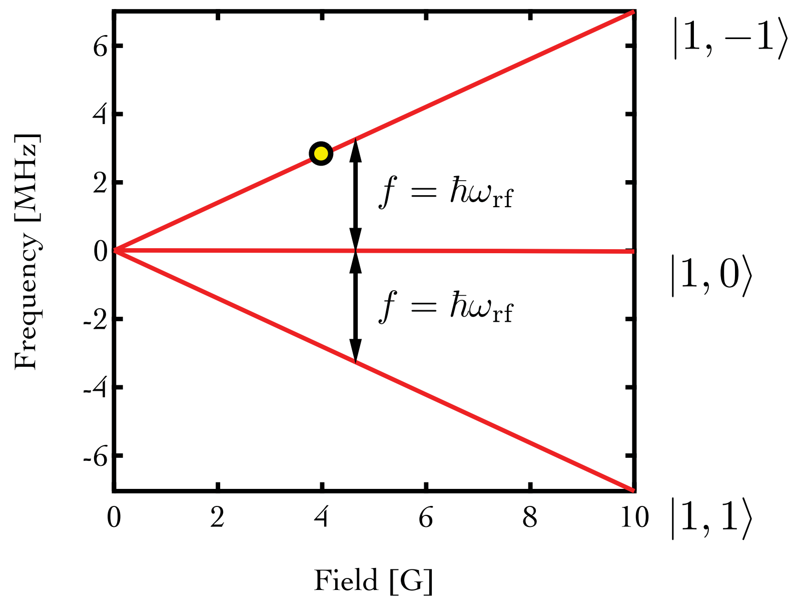

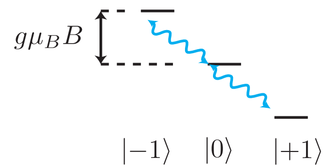

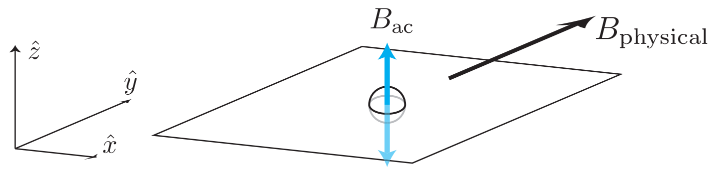

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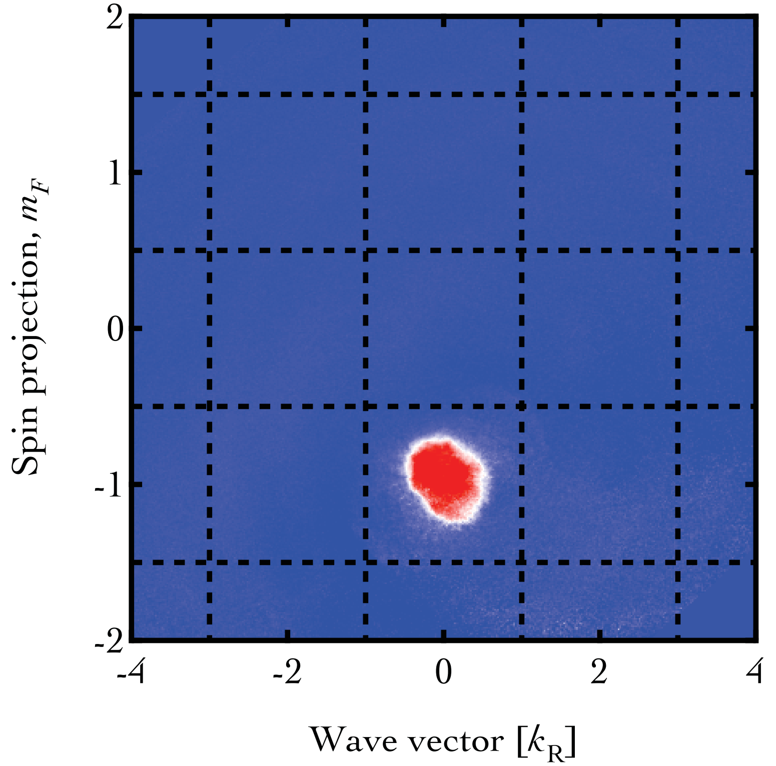
RF dressed state (RF on, ramp B to resonance)



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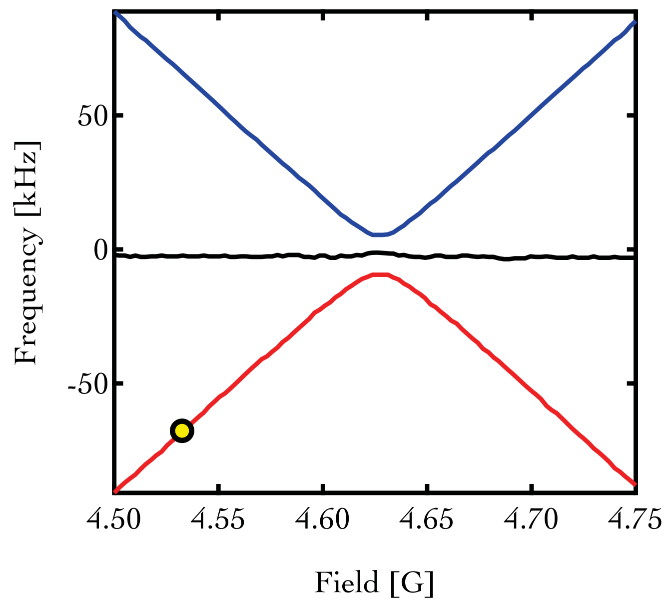

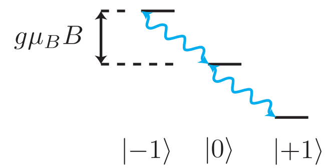

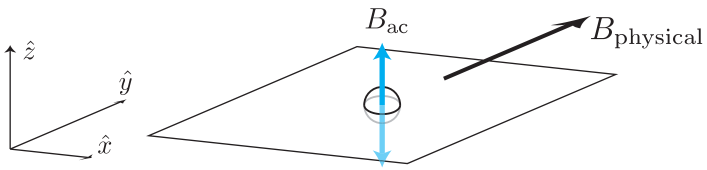

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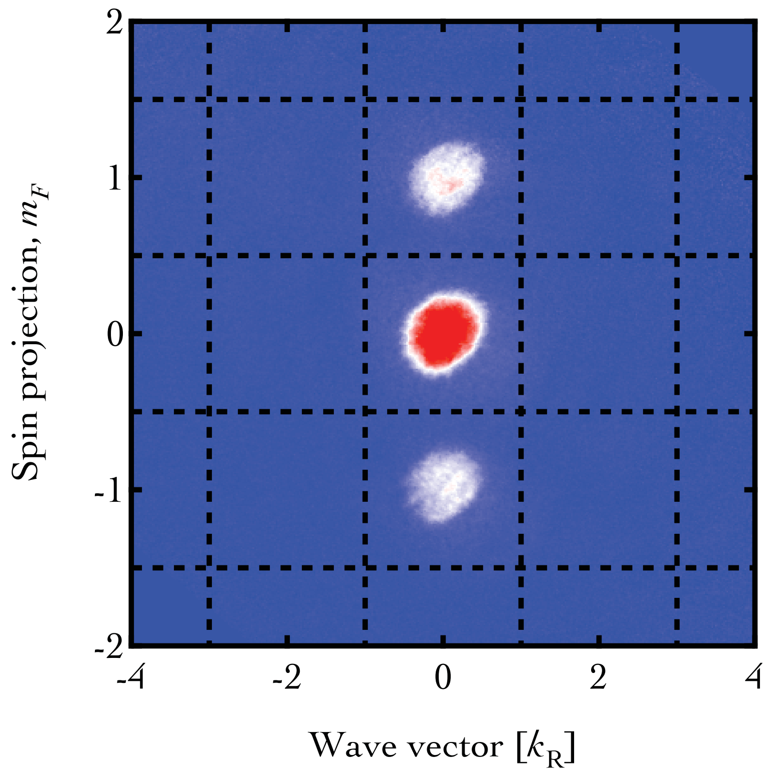

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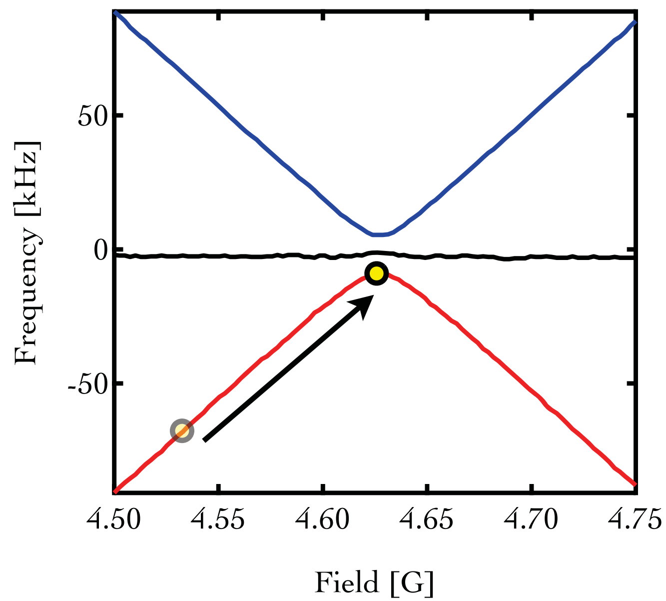
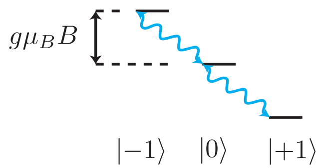
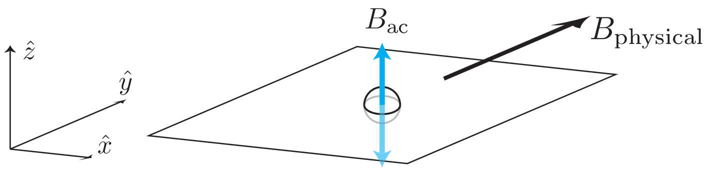




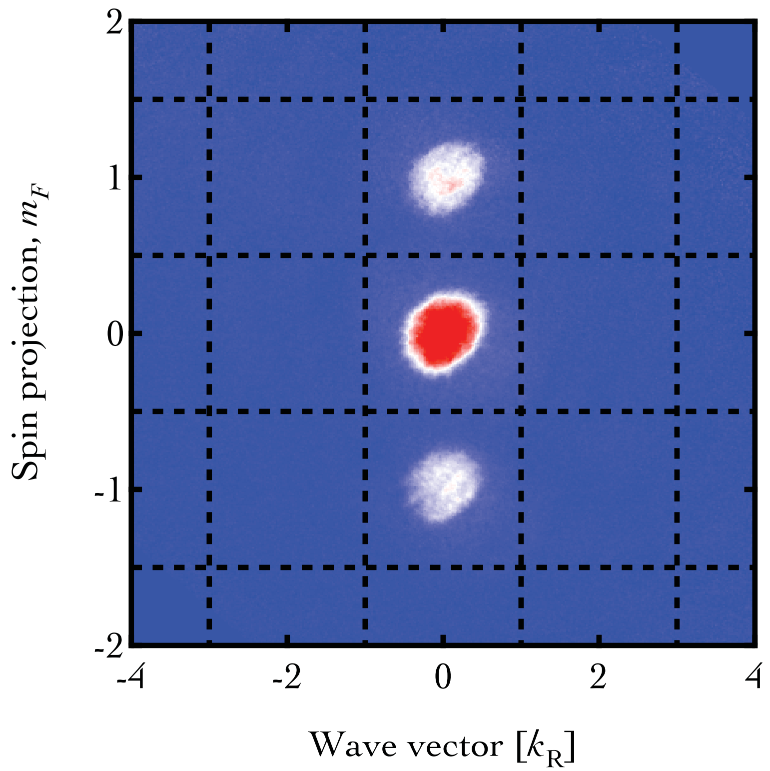


Loading: momentum

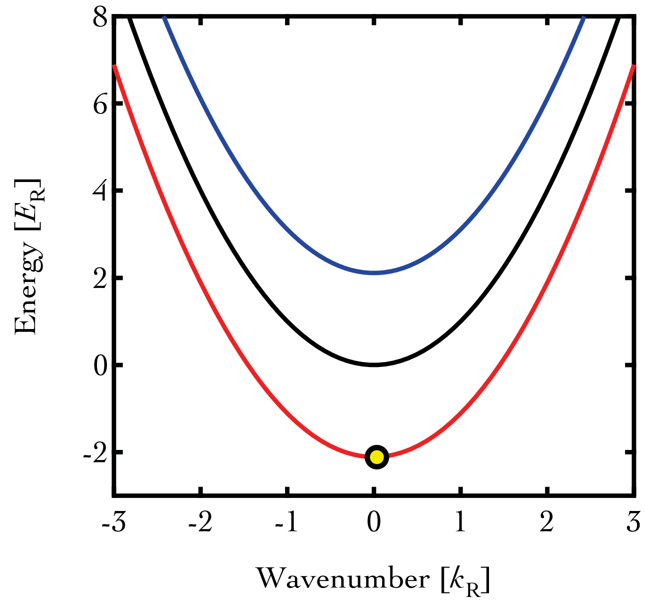
Adiabatic manipulation of atoms

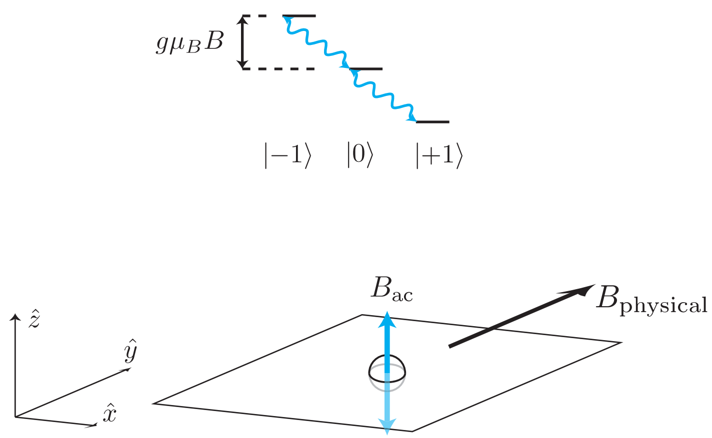
Initial state $|F = 1, m_F = -1\rangle$

RF dressed state (RF on, ramp B to resonance)



RF Dressed





Loading: momentum

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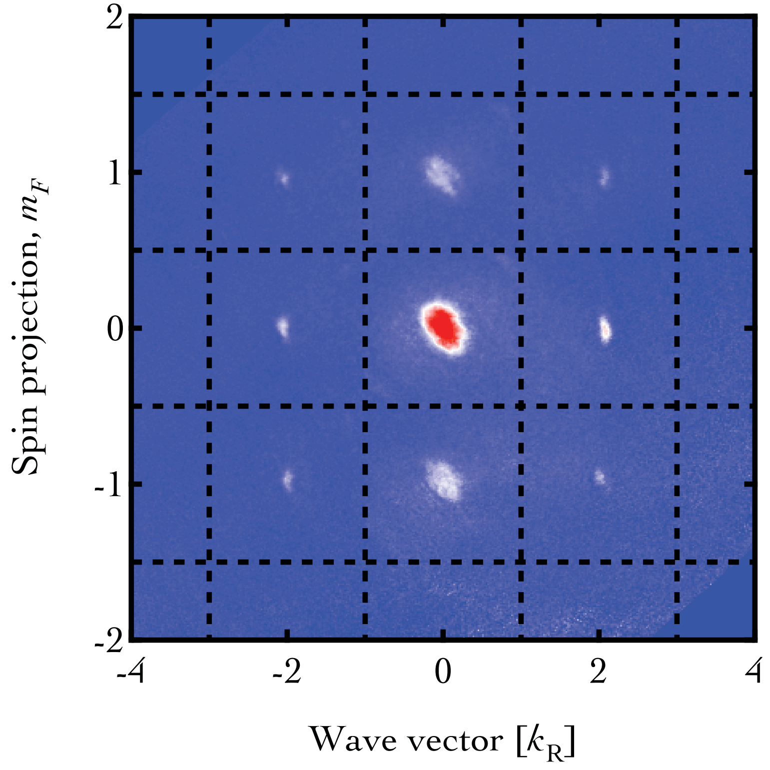
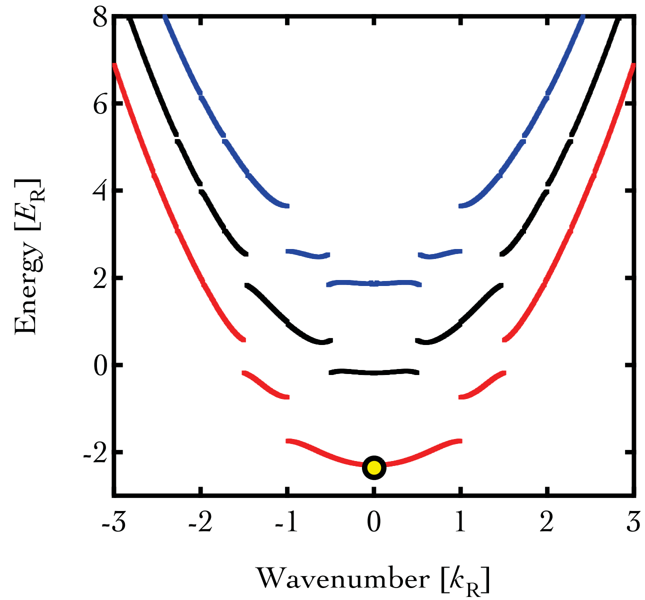
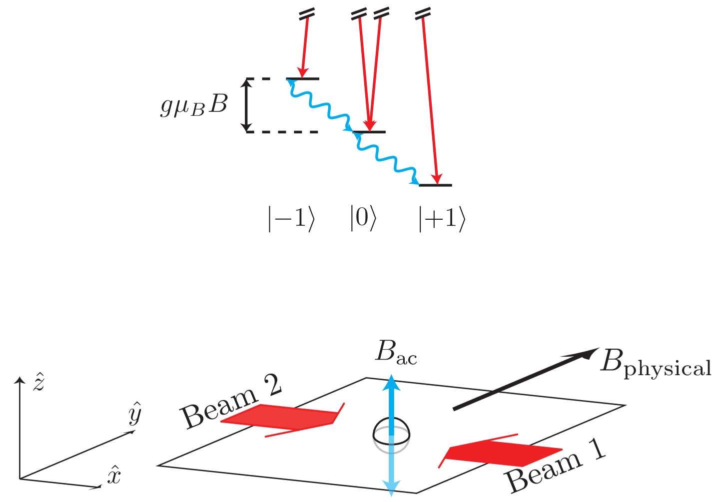
Raman + RF dressed state (Ramp Raman on)



Raman + RF Dressed





Loading: momentum

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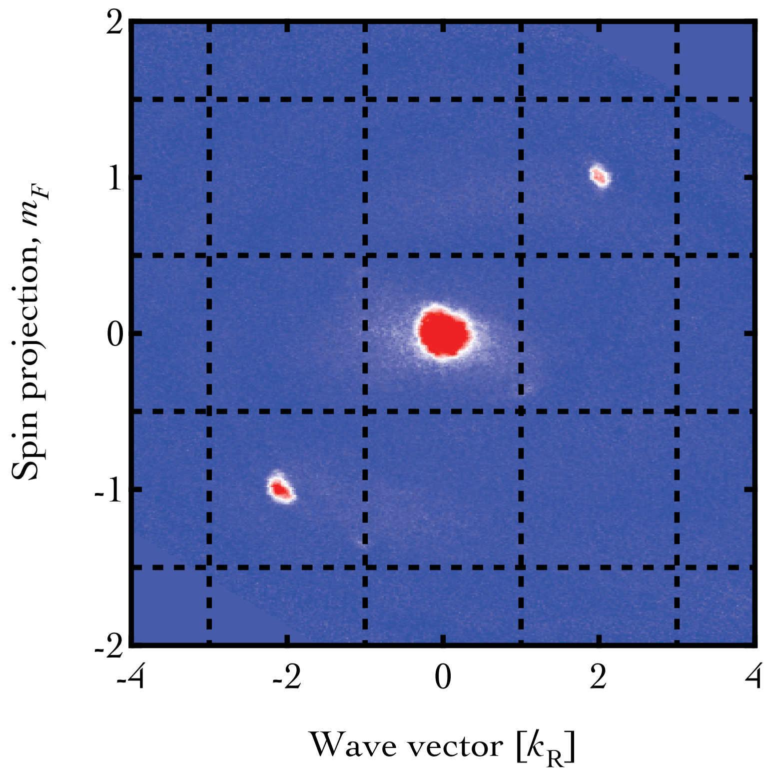
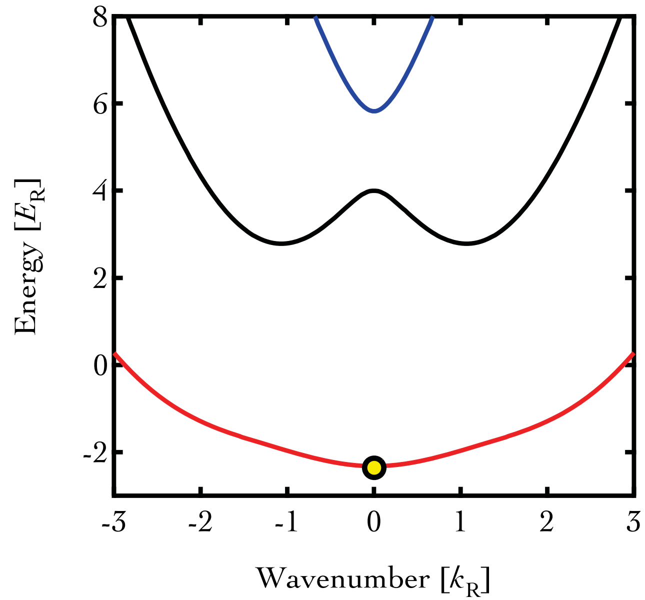
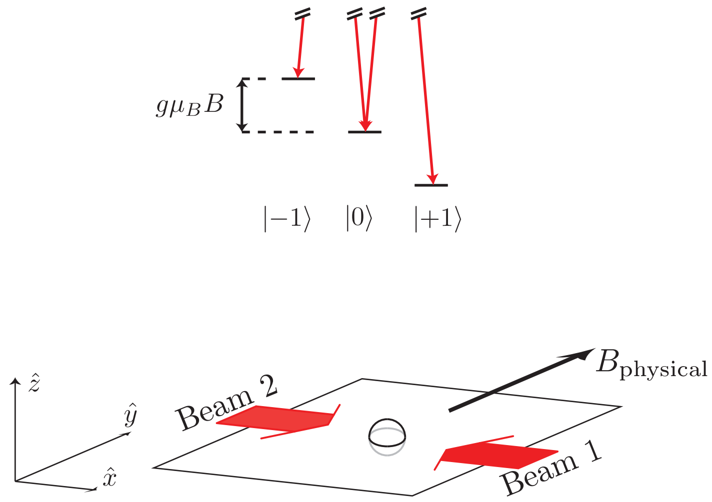
Raman only dressed state (Ramp RF off)



Raman Dressed





Displaced momentum distribution

Adiabatic manipulation of atoms

Initial state $|F = 1, m_F = -1\rangle$

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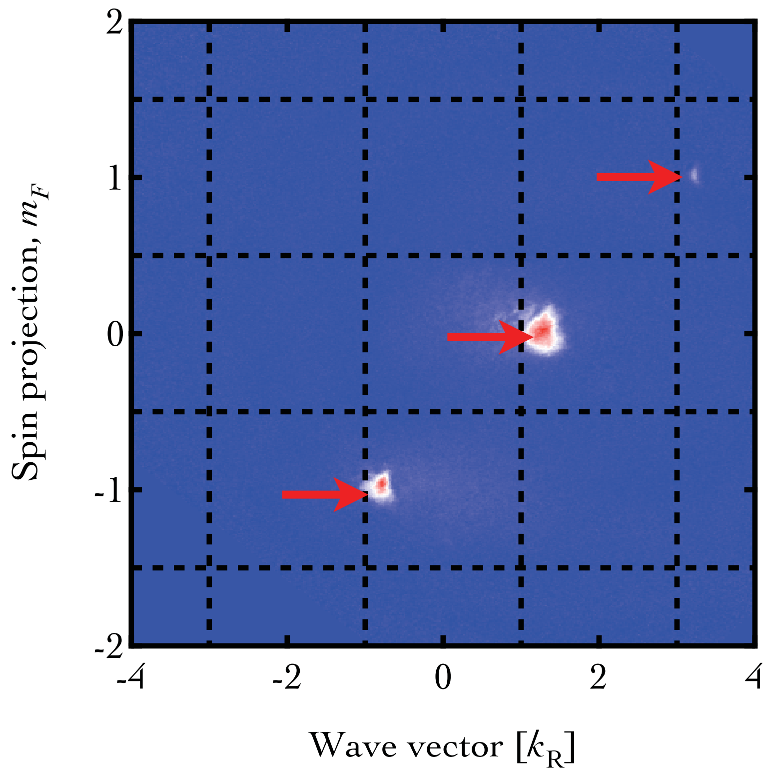
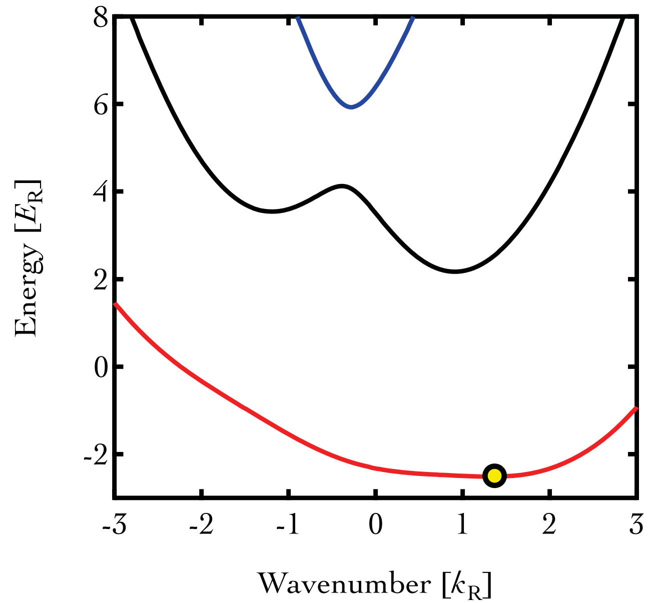
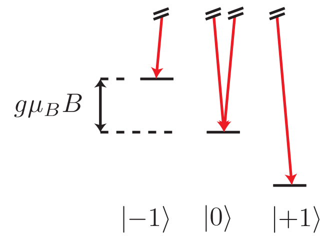
Raman + RF dressed state (Ramp Raman on)

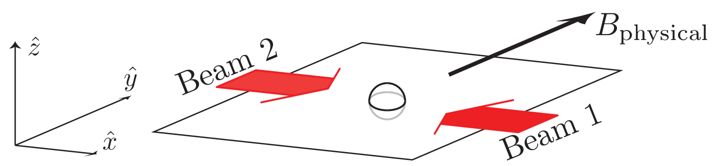
Raman only dressed state (Ramp RF off)



Raman Dressed







Displaced momentum distribution

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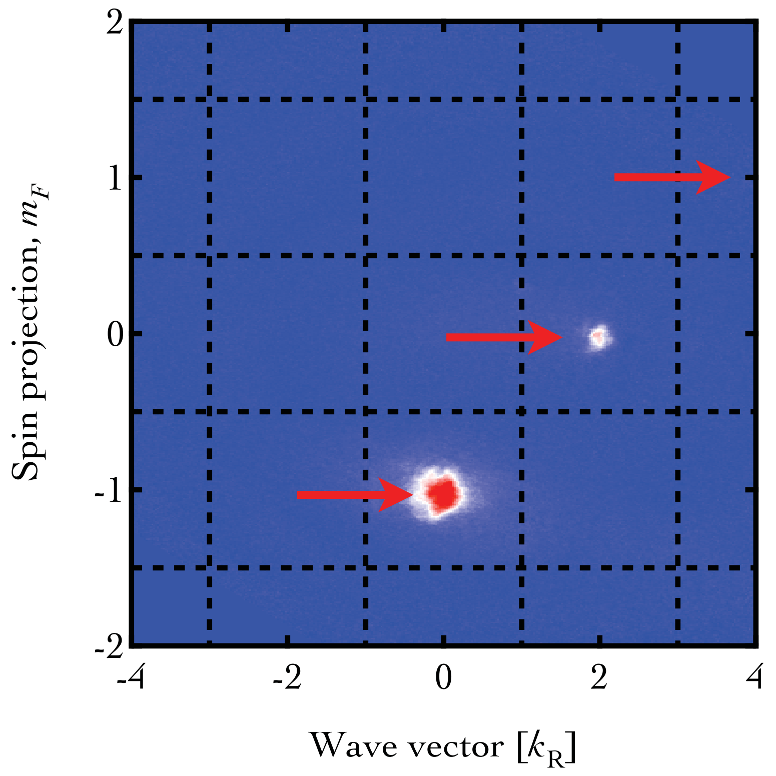
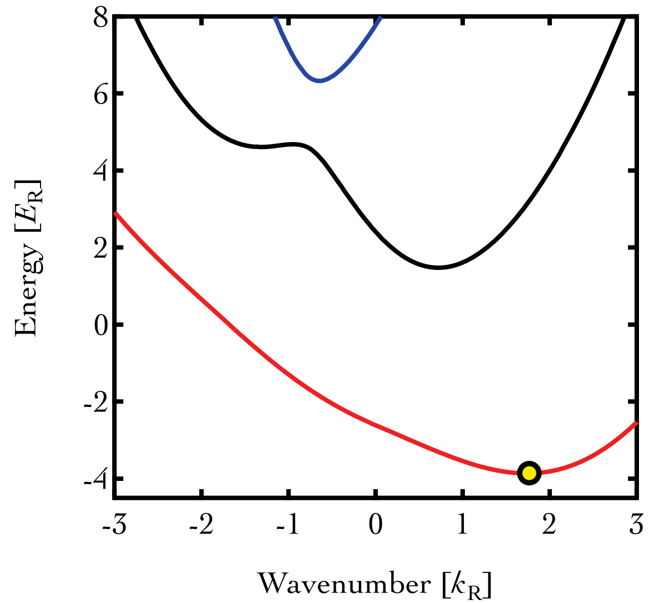
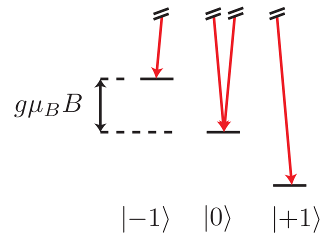
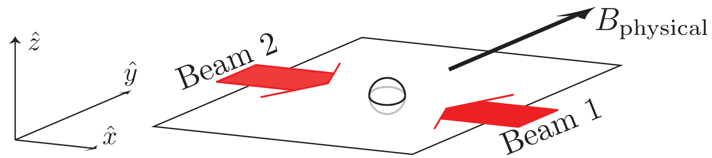
Raman only dressed state (Ramp RF off)



Raman Dressed



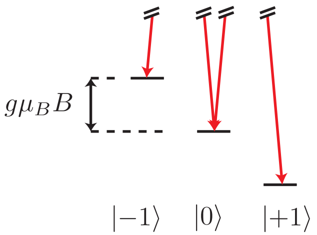


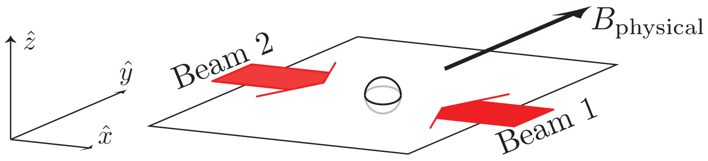


Reminder: dressed state vector potential

Raman Coupling

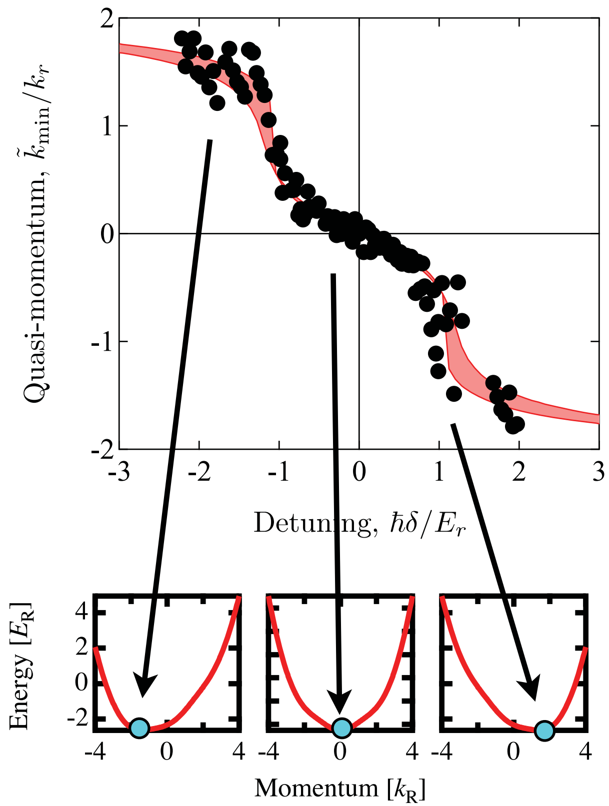
Raman coupling between ground state manifold: "dressed" Energy-momentum curves.





$E(k)$ minimum (large coupling)

Good agreement with theory



References

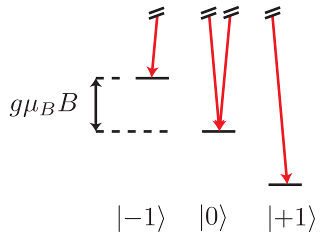
[1] Experiment: Y.-J. Lin et al, PRL **102** 130401 (2009)

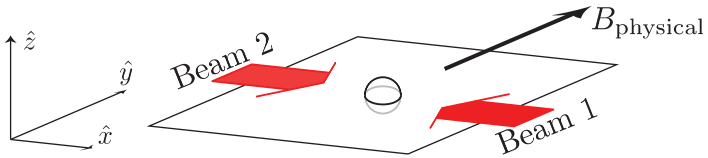
[2] Theory: IBS (Submitted to PRA)

Neat digression: experiment

Raman Coupling

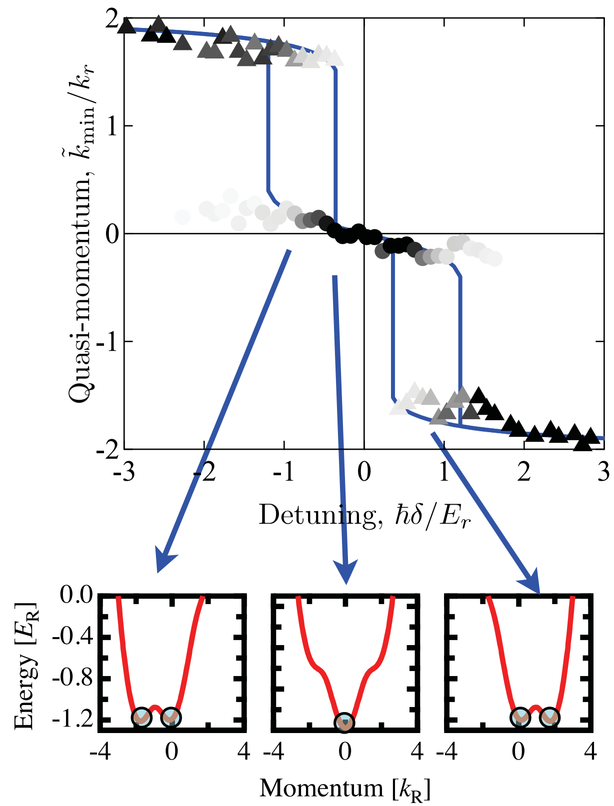
Raman coupling between ground state manifold: "dressed" Energy-momentum curves.





$E(k)$ minima (smaller coupling)

Still good agreement with theory



References

[1] Experiment: Y.-J. Lin et al, PRL **102** 130401 (2009)

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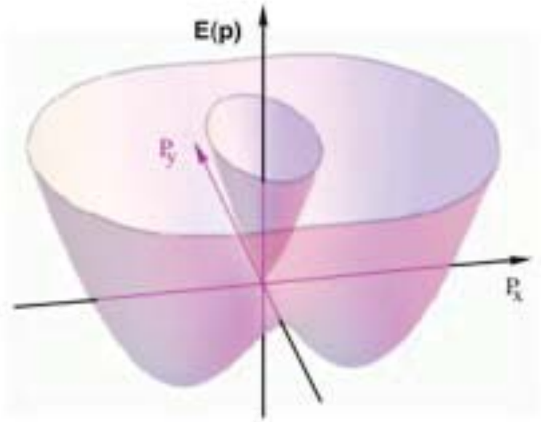
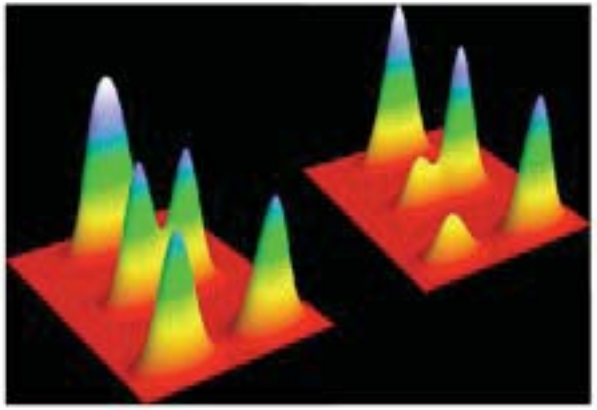
Neat digression: theory

<u>Geometry</u>



<u>Two component BEC's</u>

Hey! This what we see.

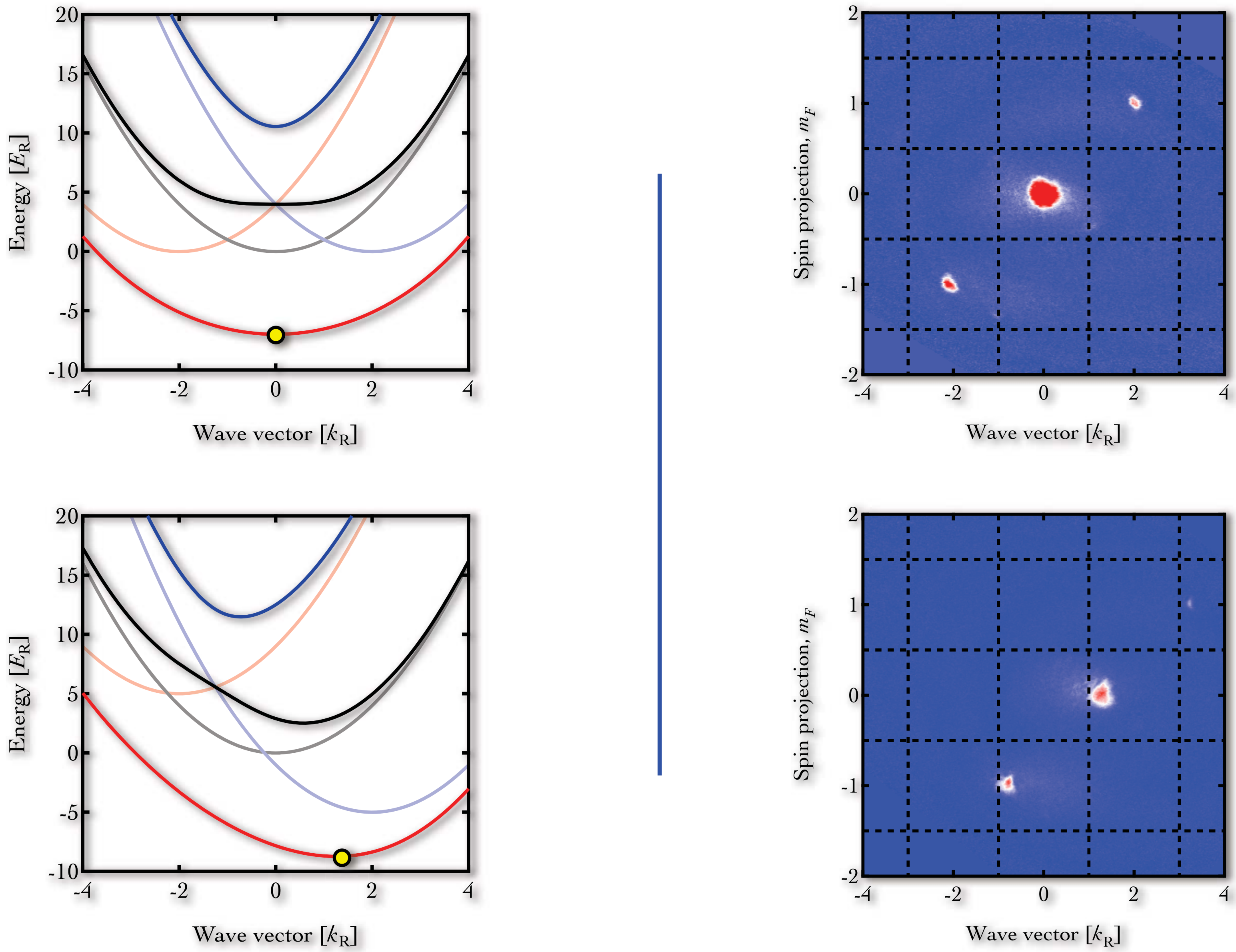


x Momentum

<u>References</u>

[1] T. Stanescu and V. Galitski, Phys. Rev. A **78**, 023616 (2008)

Atom light interaction: Summary

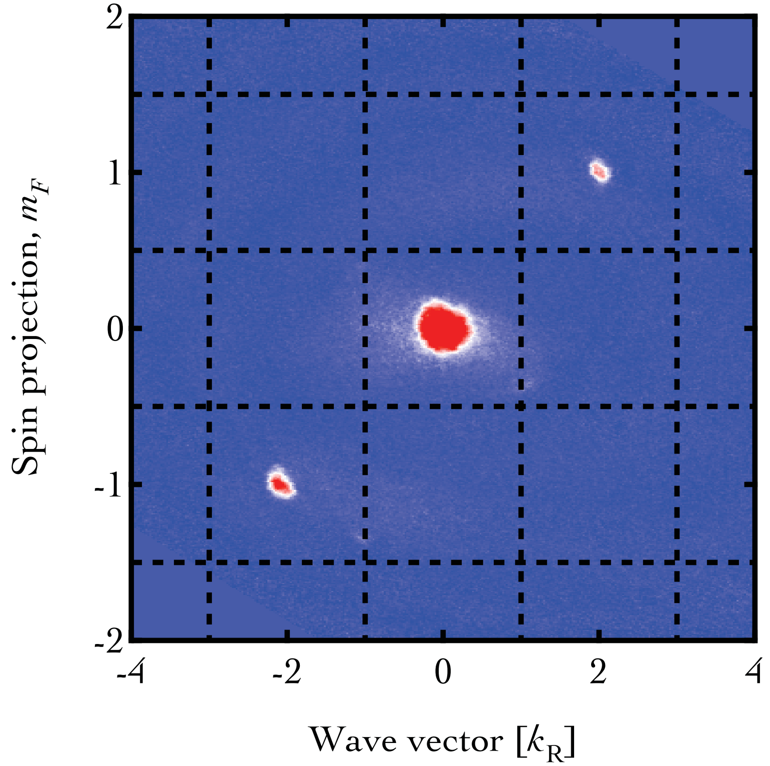


Symmetric case

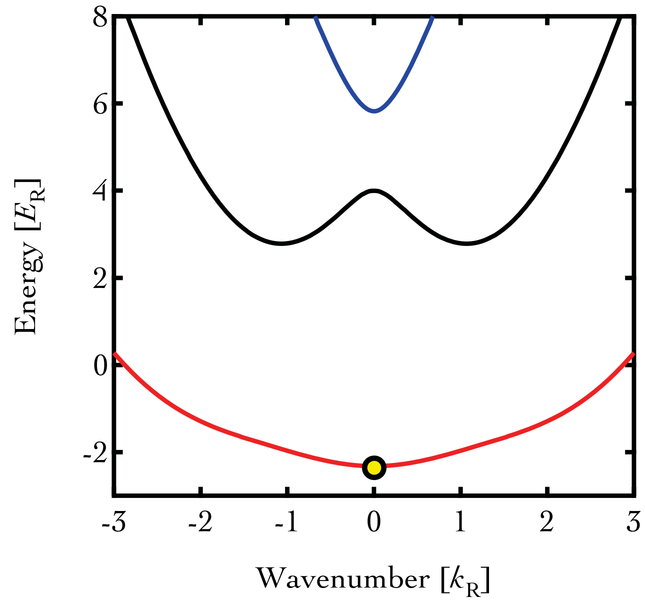
Conserved

Abrupt turnoff conserves mechanical momentum

Mechanical momentum is averaged over all orders and is zero in equilibrium (of course).



Raman Dressed



Displaced momentum distribution

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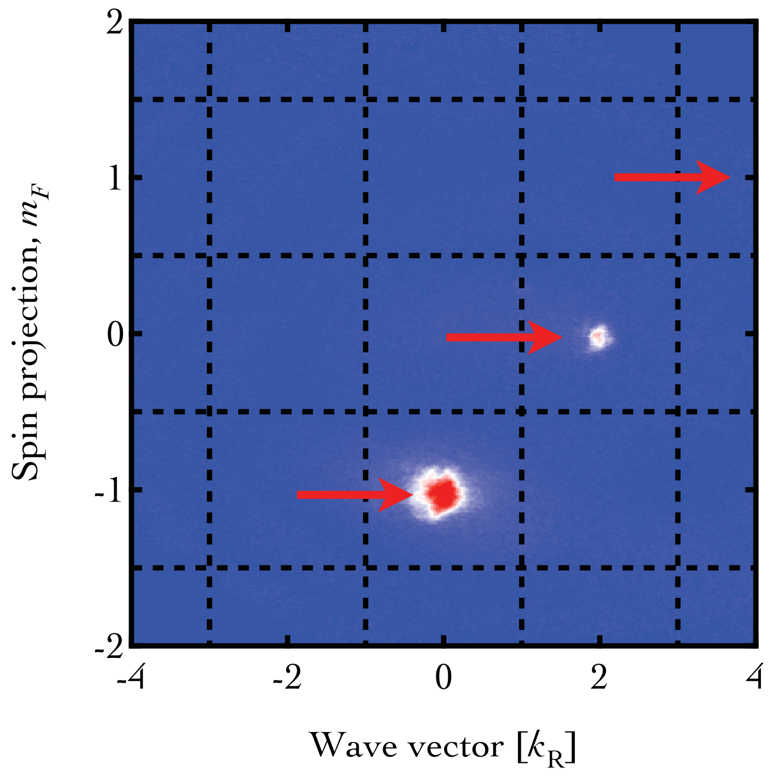
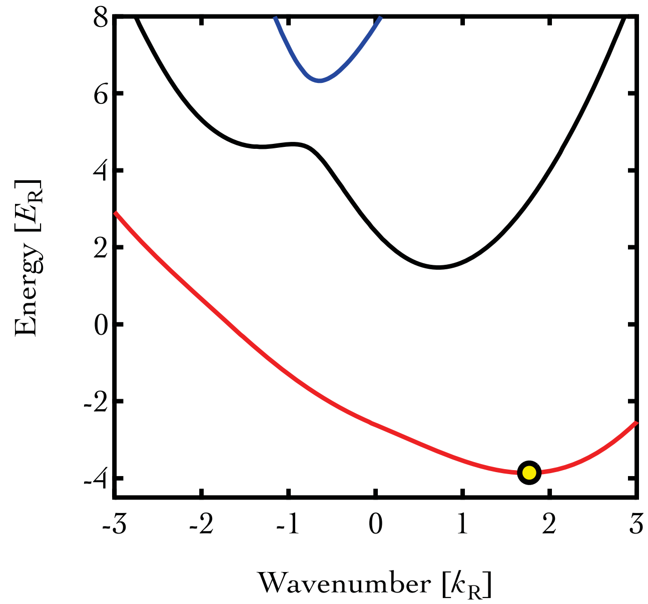


Raman Dressed



Group velocity

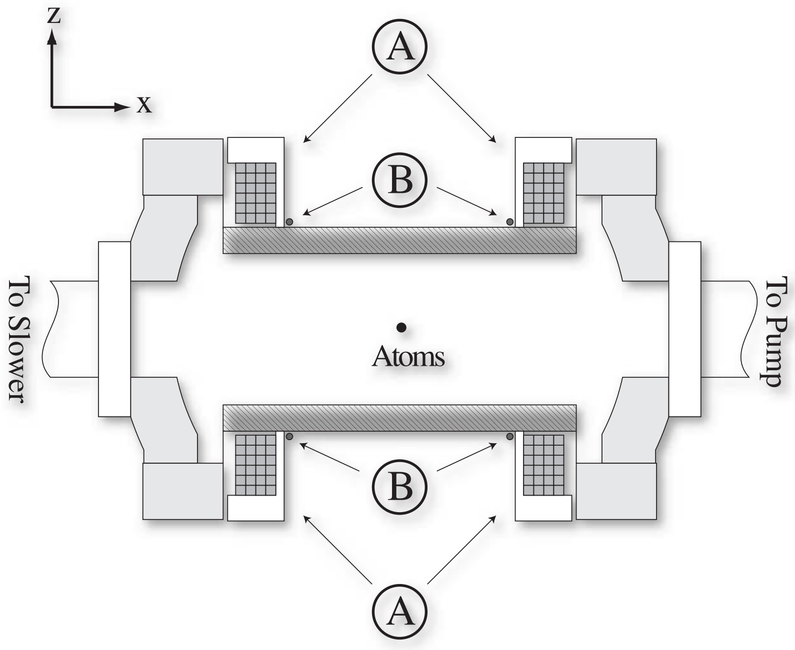
Since the 1st derivative is zero, a wave-packets group velocity is zero: no COM motion.

Main point

Idea

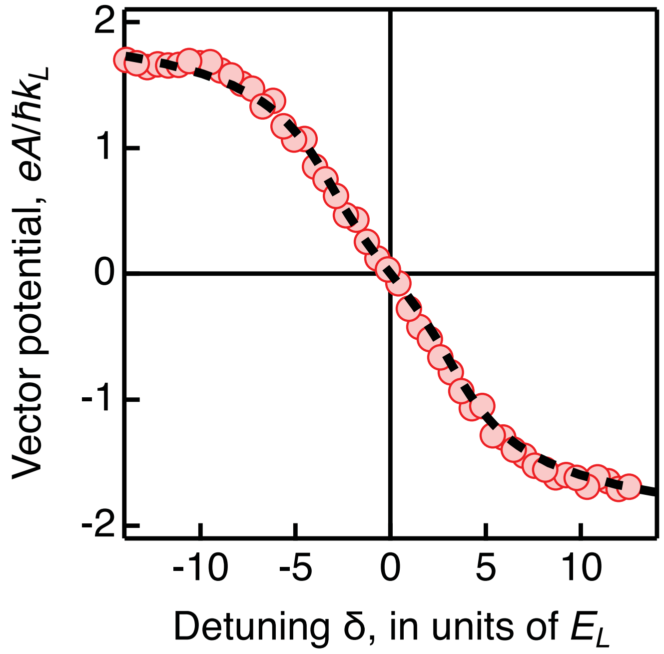
We can control the *synthetic* vector potential in time and space.

Bias and quadrupole ***B*** fields = offset and gradient in detuning.



Transfer function

A given *local* detuning specifics the local synthetic vector potential



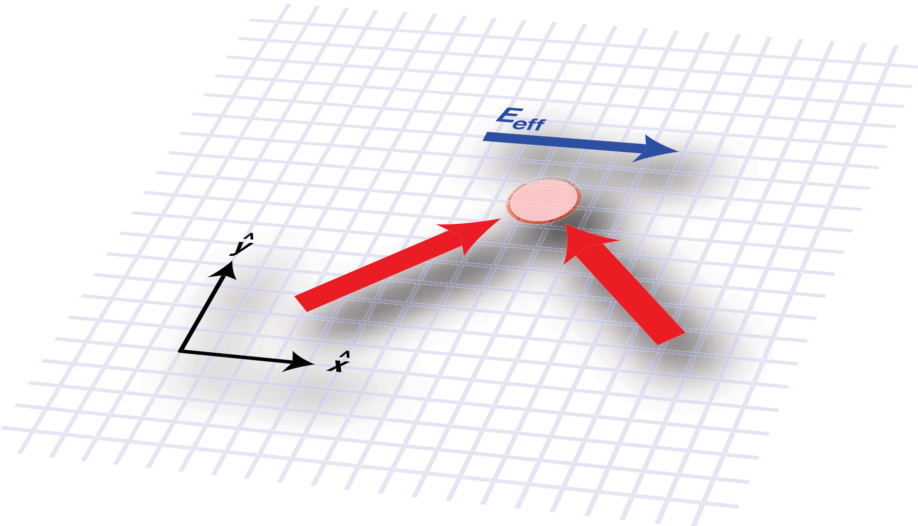
References

[1] Y.-J. Lin et al, Submitted to PRA

Electric fields

Complete disclosure

Our beams now intersect at 90°



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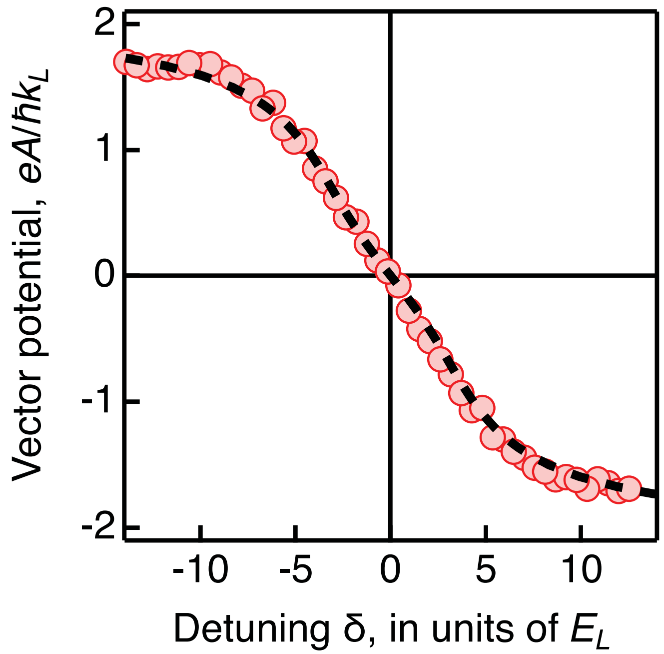


Synthetic Electric Field

A uniform vector potential: forces

Time dependence gives electric fields and forces

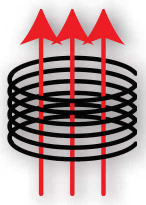
Make usual "quasi-static assumptions"

$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t}$$

$$\Delta \mathbf{k} = \frac{e}{\hbar}\int \mathbf{E} dt = -\frac{e}{\hbar}\Delta\mathbf{A}$$

Mechanical not canonical momentum

Simple geometric example from grade-school



Realization with dressed states

Synthetic Electric Field

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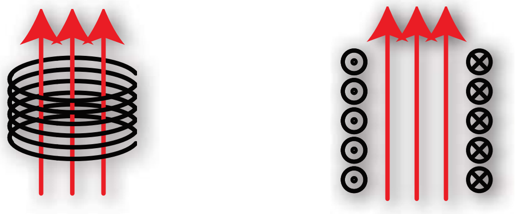

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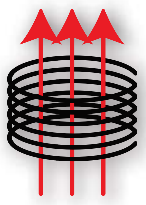

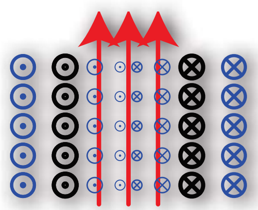

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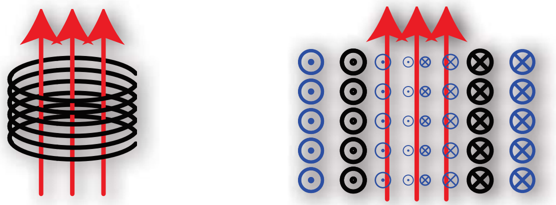
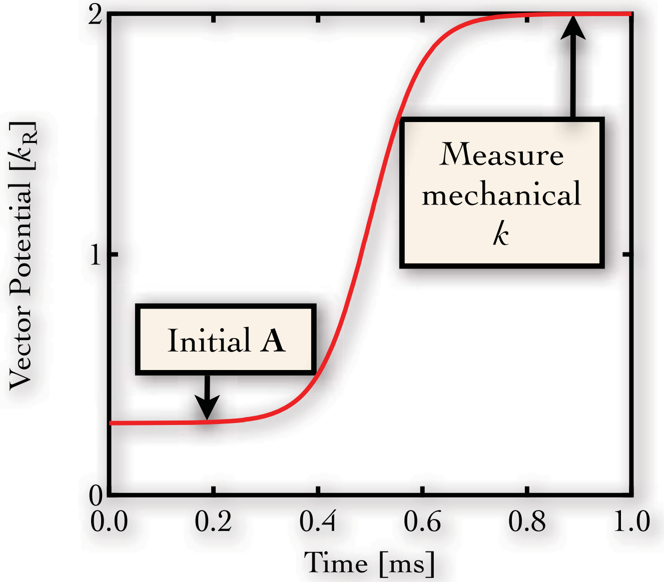


Realization with dressed states

Experimental procedure

1. Prepare initial state
2. Jump vector potential, always to $k = 2k_R$
3. Measure mechanical momentum



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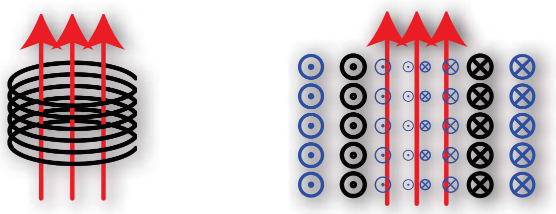
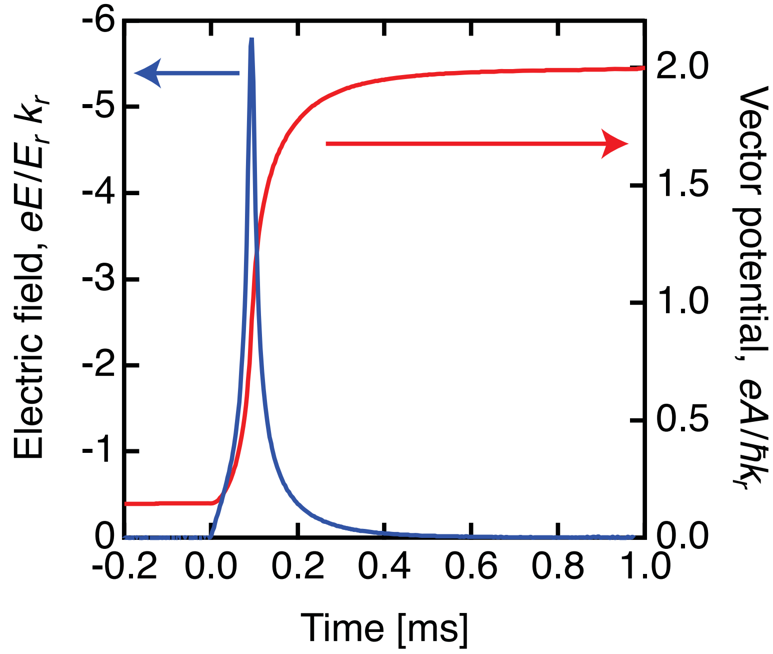


Realization with dressed states



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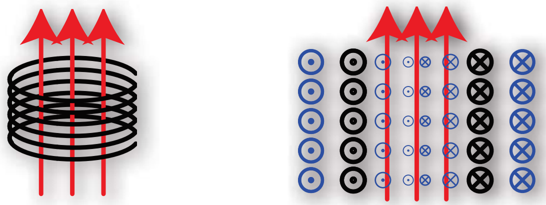
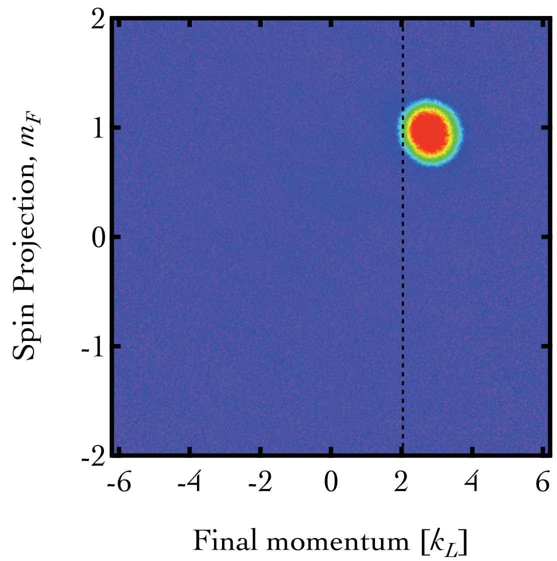


Realization with dressed states

Yes! Atoms acquire expected -2 k_R mechanical momentum kick.



Our synthetic vector potential behaves just like the real thing

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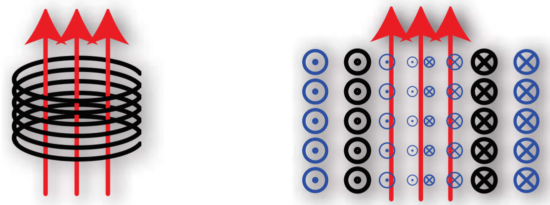

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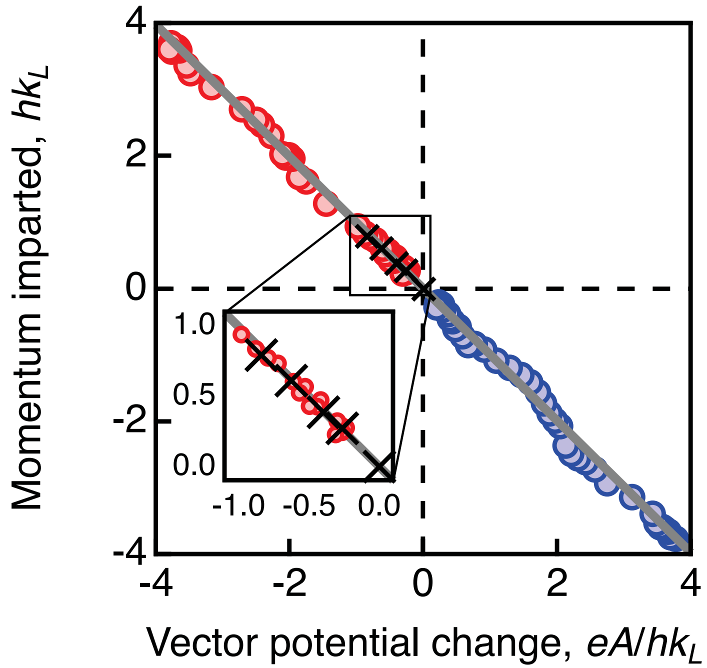
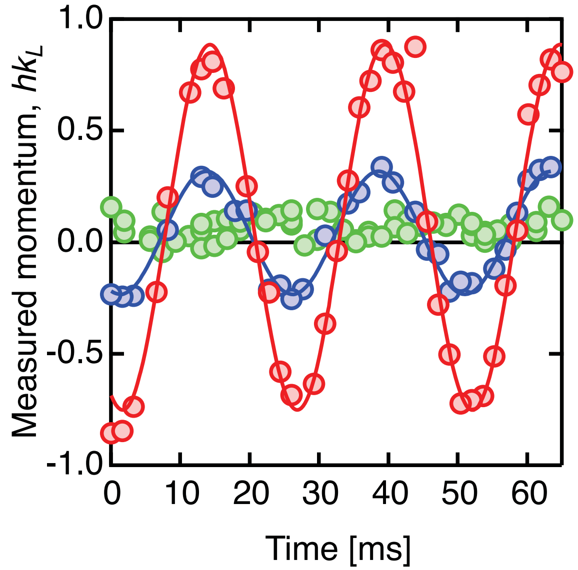
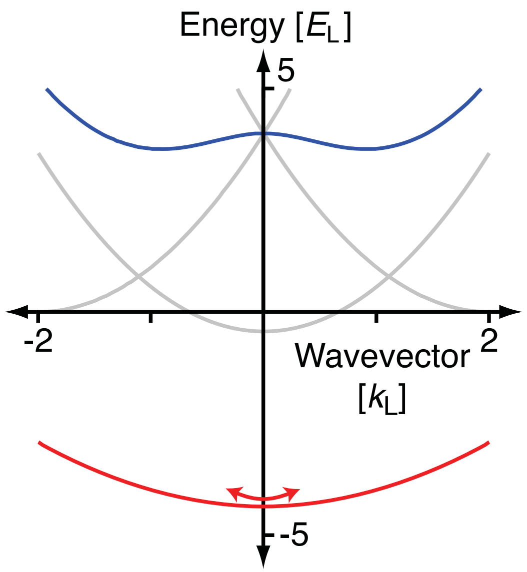
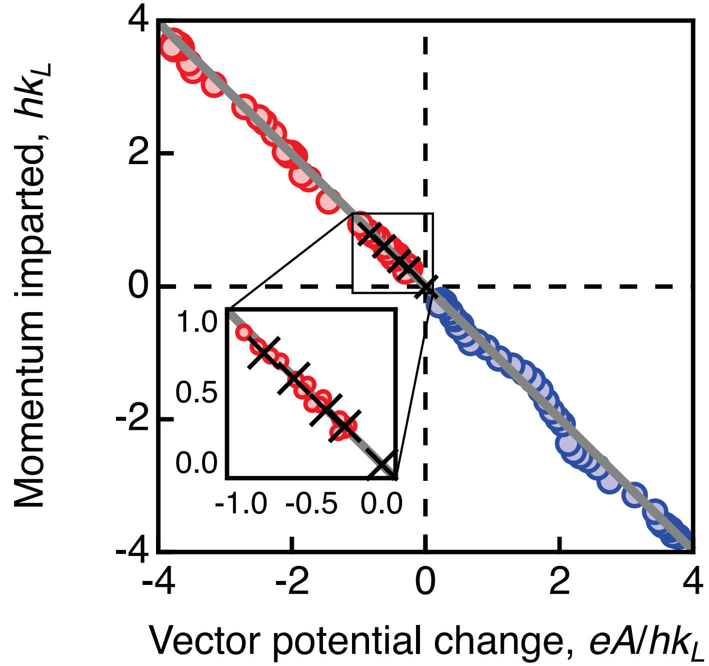


Our synthetic vector potential behaves just like the real thing

Field in the dressed state



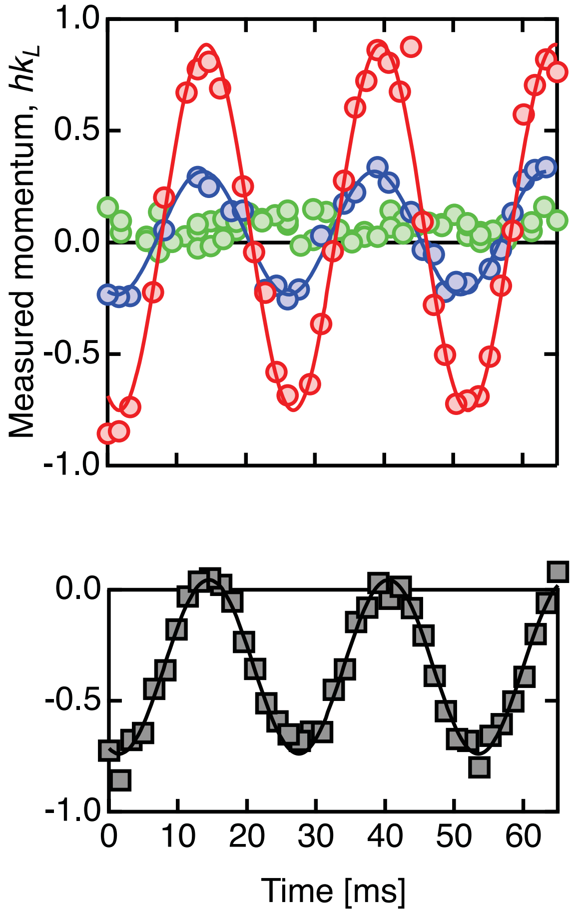


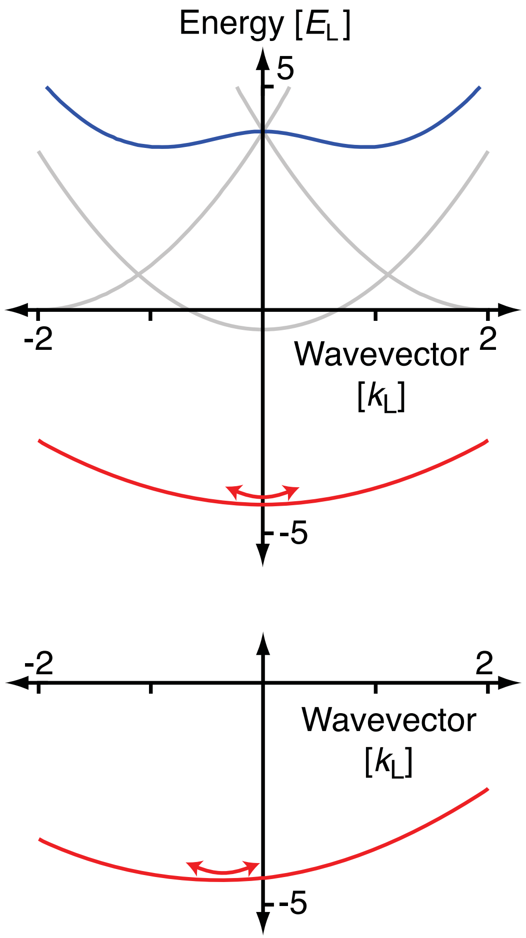


<u>Motion in dressed state</u>

Even remaining in the dressed state the atoms feel the expected electric field "kick"

Field in the dressed state: non-zero final A





<u>Motion about non-zero k</u>

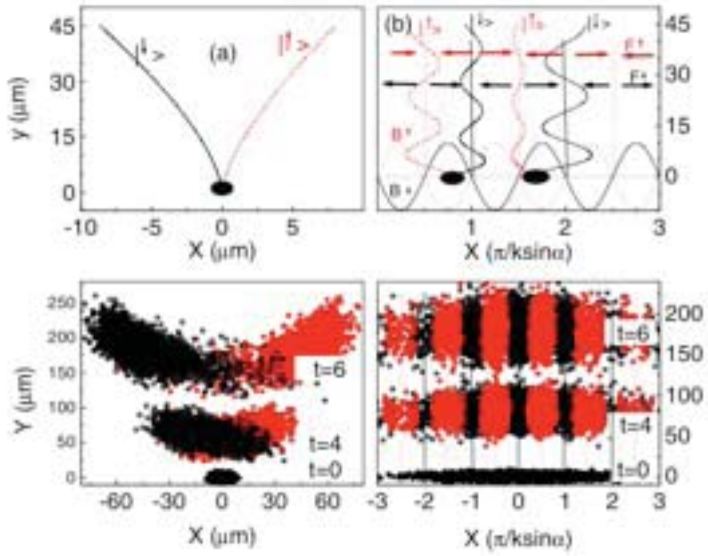
We really do measure effective canonical momentum in a specific gauge.

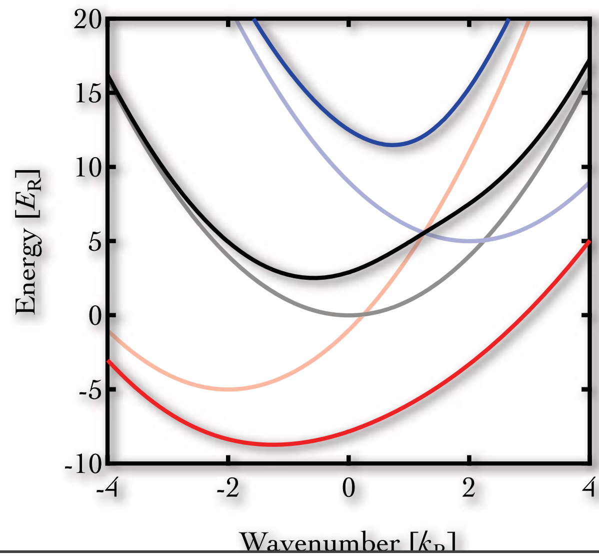
Remember canonical momentum is always an "observable" just not unique.

"Mechanical" momentum remains about zero.

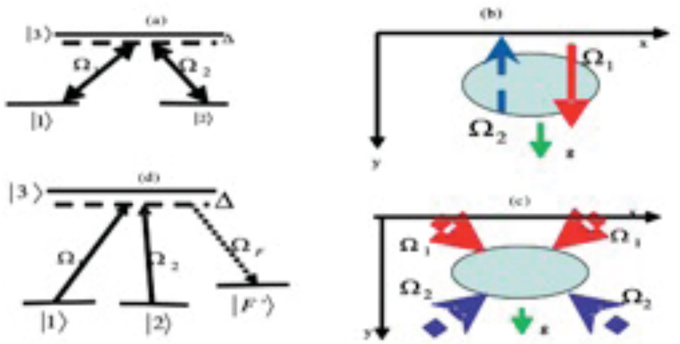
Other applications: spin-Hall physics

Theory: "spin" dependant forces





Geometry



References
[1] Shi-Liang Zhu et al., PRL **97** 240401 (2006)

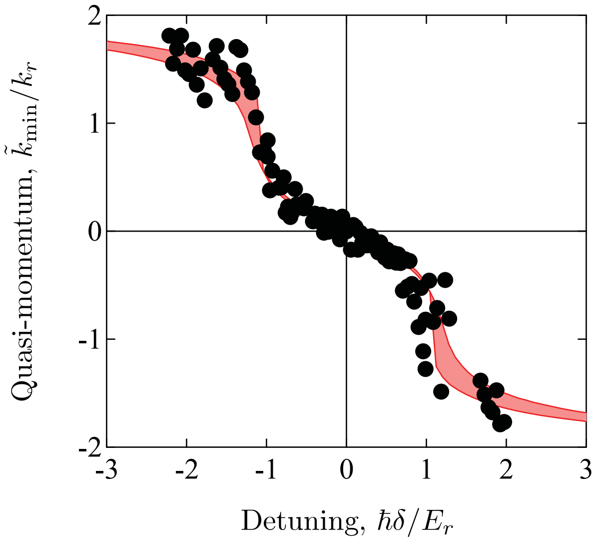
New approaches for controlling cold atoms

We have been working on controlling terms in the *kinetic* energy.

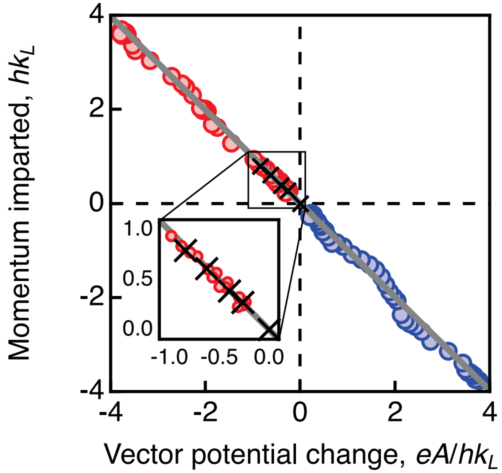
Not discussed today
Control of m^*:
From 1 to ∞, and negative

$$\hat{H} = \sum_j \left[\frac{\hat{p}_j^2}{2m} + V(x_j) \right] + \sum_{i<j} U(x_i - x_j)$$

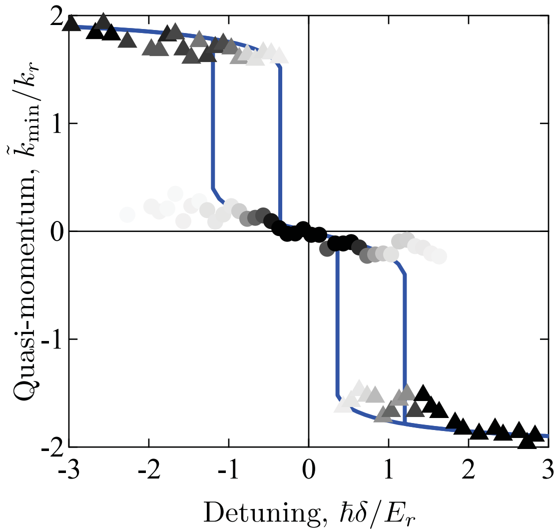
Synthetic vector potential



Synthetic electric field



Momentum double well



Our References
[1] Experiment: Y.-J. Lin et al, PRL **102** 130401 (2009)
[2] Electric field: in preparation
[3] Theory: IBS (Submitted to PRA)

Next experimental step: spatial gradients (in progress)

Adiabatic manipulation of atoms

(1) Stabilize external magnetic fields and gradients
(reduce unwanted heating and stabilize dressed state)

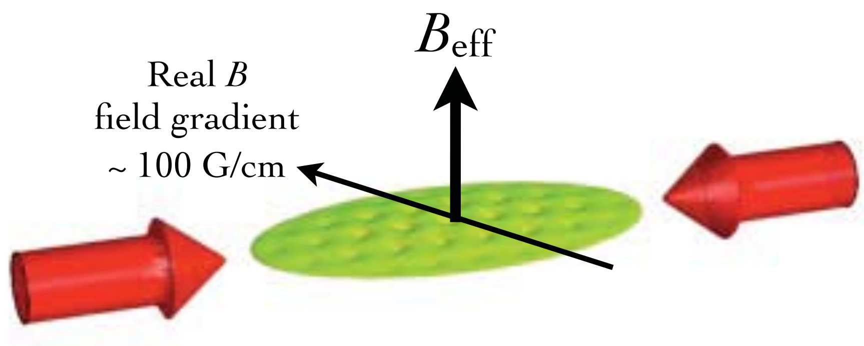
(2) Phase and intensity lock Raman coupling lasers
(stabilize dressed state)

(3) Make dressed state actually dark
(our system has both D1 and D2 excited states, but there exists a "real" dark state configuration detuned between D1 and D2)

System

Start with a 2D BEC

Add Raman fields and **a spatial gradient** to create an effective magnetic field



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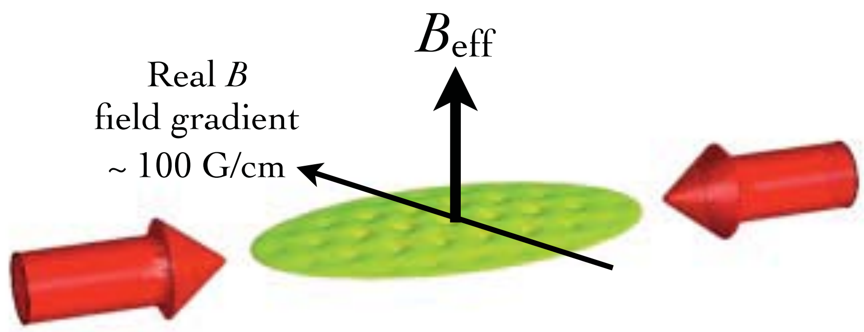
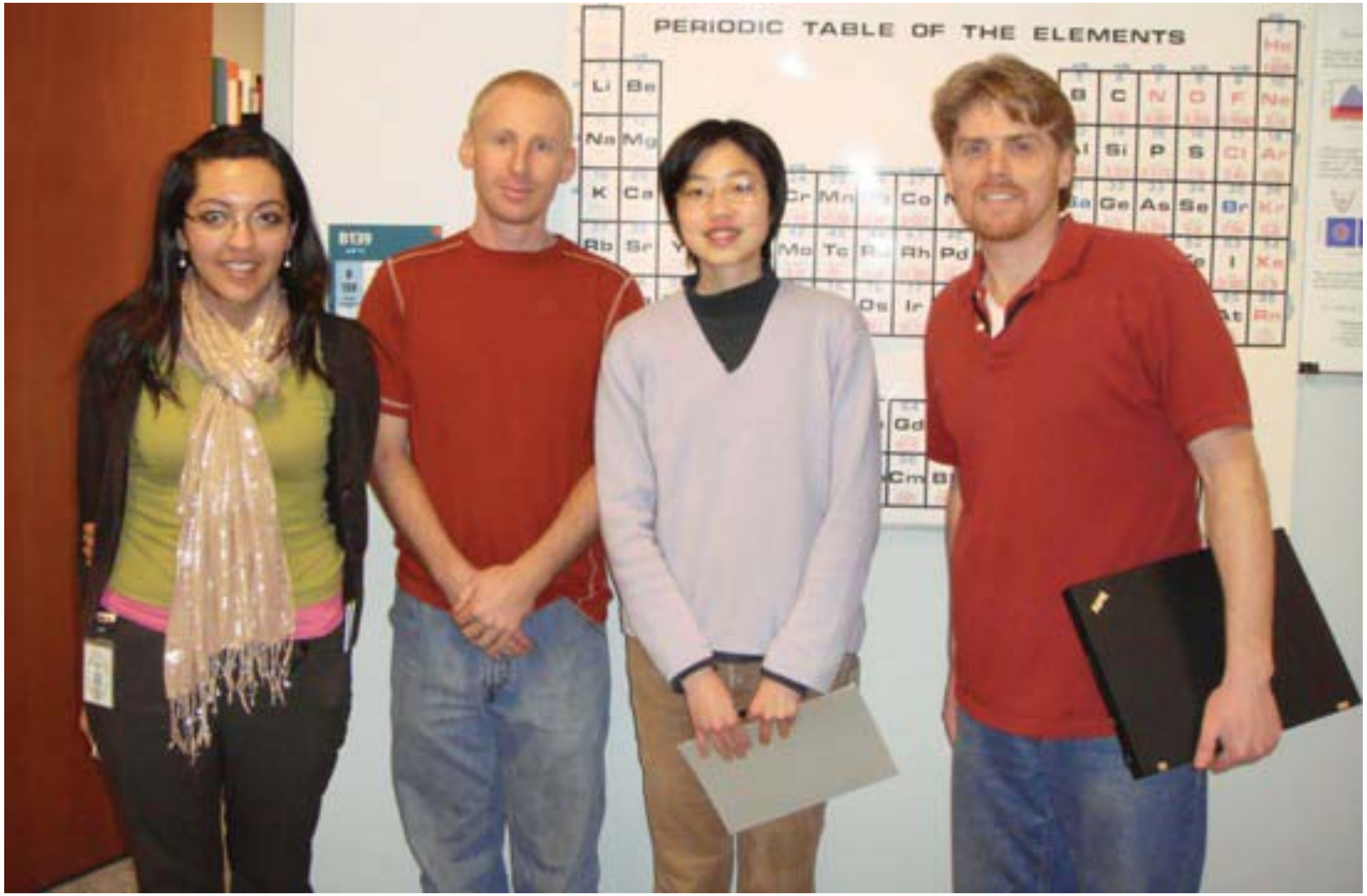


In the lab!



Karina *"RF Slicer"* Jimenez-Garcia | IBS | Yu-Ju *"Fake fields"* Lin | Rob *"Feshbach"* Compton