Toshiko Yuasa Aword

Bose-Einstein Condensates with Internal Degrees of Freedom

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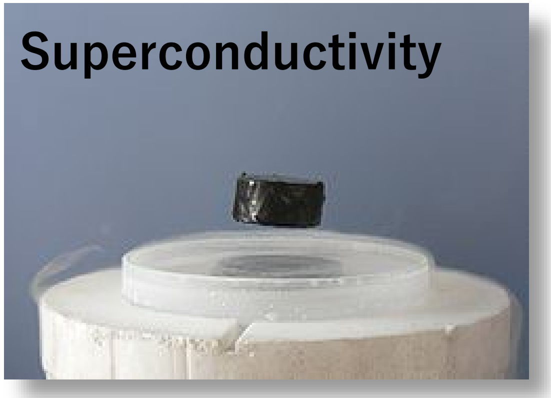
Condensed Matter Physics

Quantum Many-Body Systems exhibit exotic phenomena
that cannot be expected from single-particle physics

Metal/Insulator

Magnetism



Superconductivity

Photos from wiki

Cold-atomic Systems

- A dilute, ultra-cold gaseous ensemble of atoms

  10^{-5} x atmosphere, T<100nK

- Highly tunable quantum many-body systems: almost all parameters in Hamiltonian is tunable in experiment
- Nobel Prize in Physics awarded for development of cooling technology and realization of quantum condensed gas

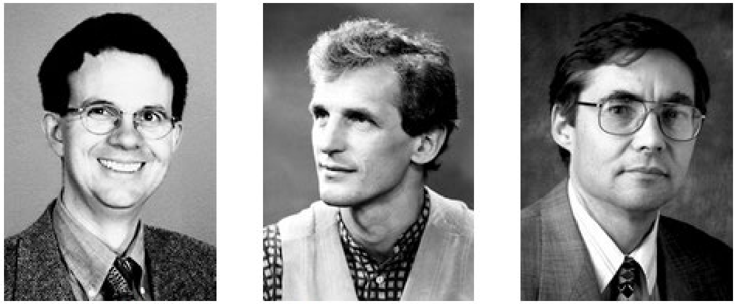

Steven Chu

Claude Cohen-Tannoudji

William D. Phillips

Nobel prize in physics, 1997

"development of methods to cool and trap atoms with laser light"


Eric A. Cornell

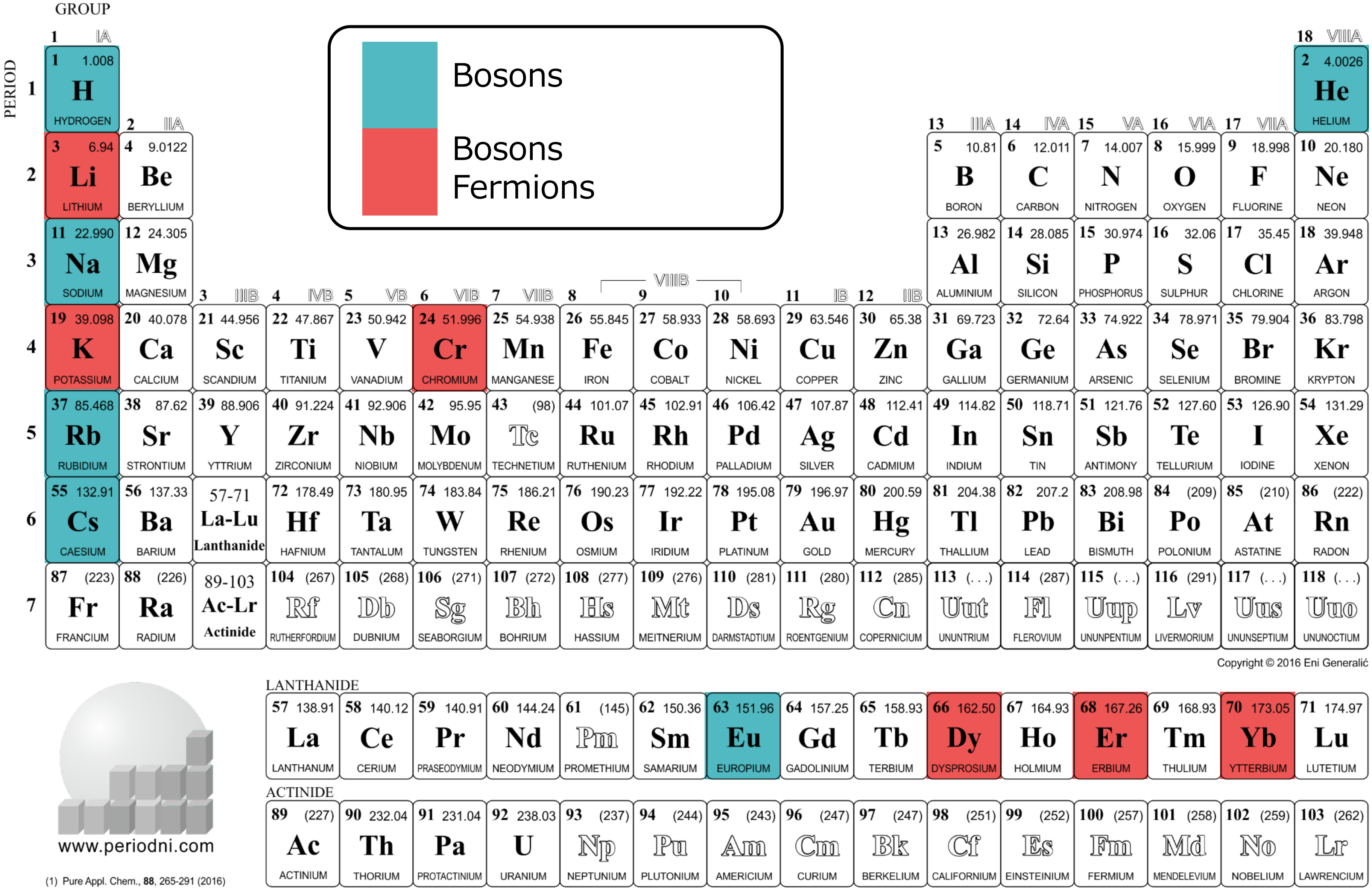
Wolfgang Ketterle

Carl E. Wieman

Nobel prize in physics, 2001

"achievement of Bose-Einstein condensation in dilute gases of alkali atoms"

Atoms Used in Cold Atomic Experiments



🟦 Bosons

🟥 Bosons
Fermions

PERIOD \ GROUP	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	🟦 1 1.008 H HYDROGEN																	🟦 2 4.0026 He HELIUM
2	🟥 3 6.94 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.81 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON
3	🟦 11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.085 Si SILICON	15 30.974 P PHOSPHORUS	16 32.06 S SULPHUR	17 35.45 Cl CHLORINE	18 39.948 Ar ARGON
4	🟥 19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	🟥 24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.38 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.971 Se SELENIUM	35 79.904 Br BROMINE	36 83.798 Kr KRYPTON
5	🟦 37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.95 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	🟦 55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (267) Rf RUTHERFORDIUM	105 (268) Db DUBNIUM	106 (271) Sg SEABORGIUM	107 (272) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (276) Mt MEITNERIUM	110 (281) Ds DARMSTADTIUM	111 (280) Rg ROENTGENIUM	112 (285) Cn COPERNICIUM	113 (. . .) Uut UNUNTRIUM	114 (287) Fl FLEROVIUM	115 (. . .) Uup UNUNPENTIUM	116 (291) Lv LIVERMORIUM	117 (. . .) Uus UNUNSEPTIUM	118 (. . .) Uuo UNUNOCTIUM

LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	🟦 63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	🟥 66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	🟥 68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	🟥 70 173.05 Yb YTTERBIUM	71 174.97 Lu LUTETIUM

ACTINIDE

89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

www.periodni.com

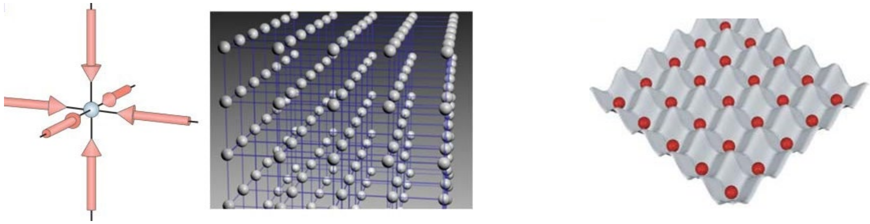
(1) Pure Appl. Chem., **88**, 265-291 (2016)

Manipulation of Atoms

Optical Lattice

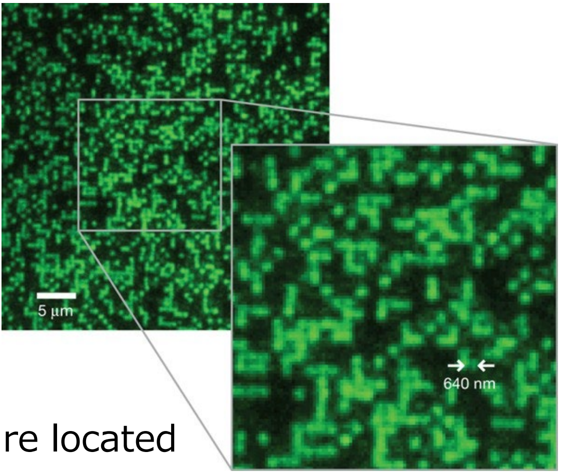
Nature Physics **1**, 23-30 (2005)

Introduce periodic potentials ↔ electrons in solids



Atomic gas Microscope

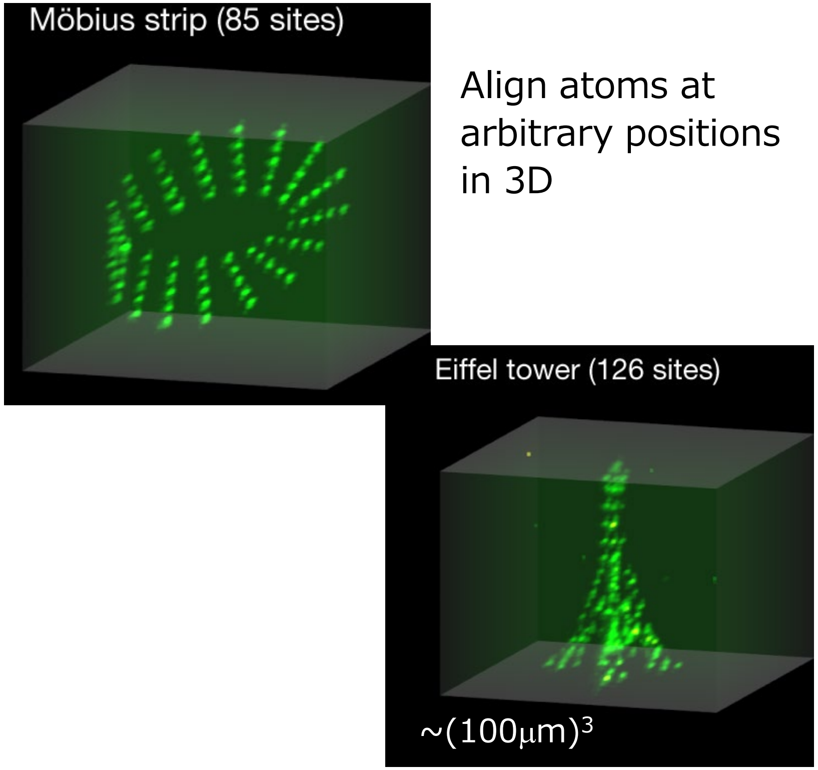
Nature **462**, 74-77 (2009)



Directly observe which sites the atoms are located

Optical Tweezer Array

Nature **561**, 79-82 (2018)



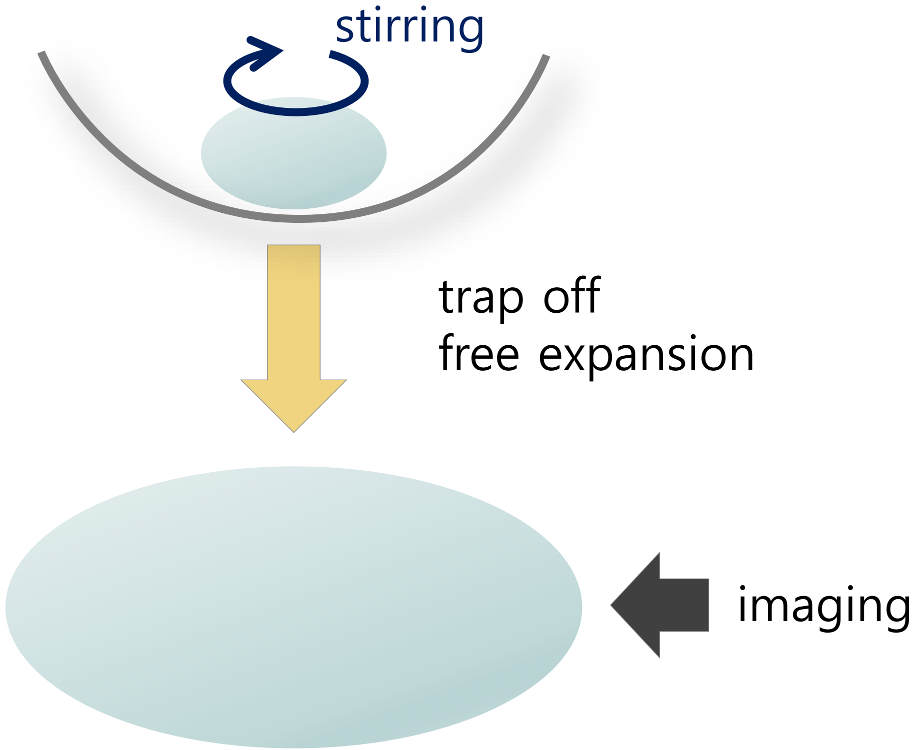
Align atoms at arbitrary positions in 3D

Bose-Einstein Condensate (BEC) of Atoms

- Bosonic atoms at low temperature
  → Bose-Einstein condensation

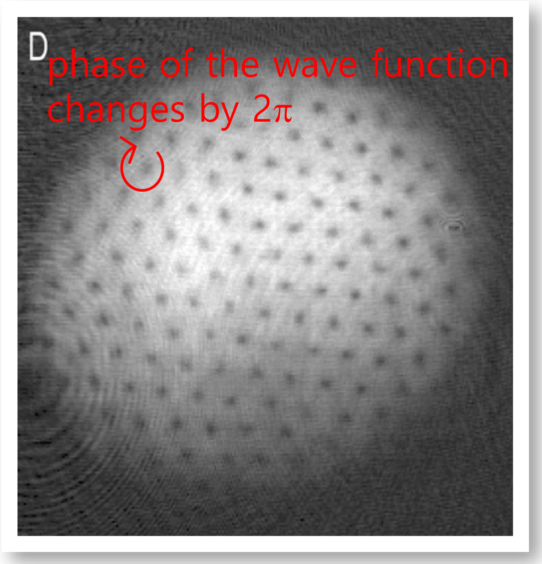
$$\Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, \cdots, \boldsymbol{r}_N) = \prod_{i=1,N} \phi(\boldsymbol{r}_i)$$

- Macroscopic wave function can be experimentally observed


stirring

trap off
free expansion

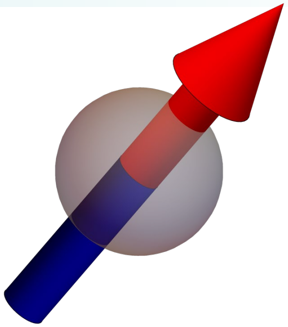
imaging



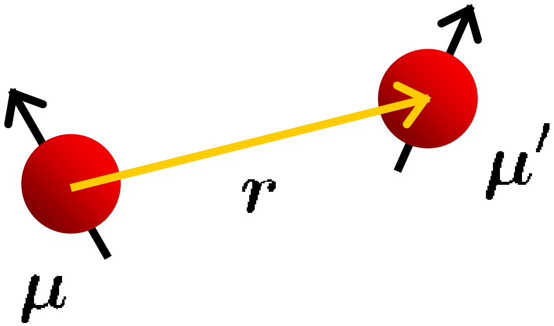
vortex lattice observed in Rb BEC
Abo-Shaeer, et al., Science (2001)

Spin Internal Degrees of Freedom

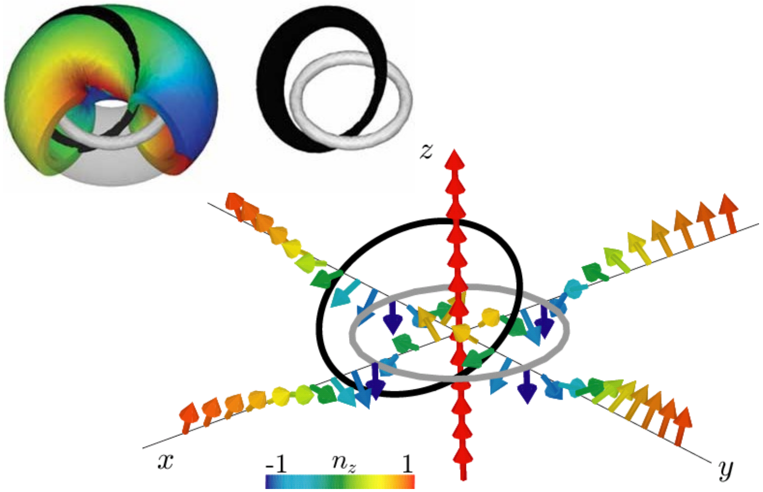
Quest for novel quantum phenomena by actively utilizing spin degrees of freedom of atoms



- BECs with magnetic dipole-dipole interactions

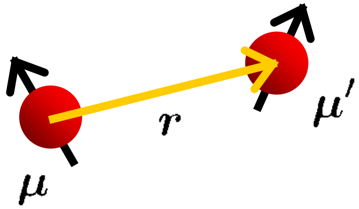


- Topological excitations in spinor BECs

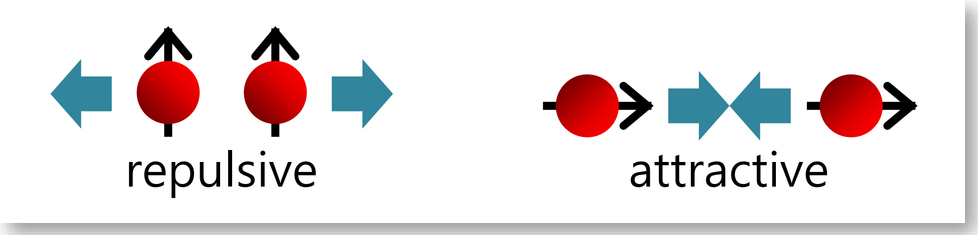


Magnetic Dipole-Dipole Interaction

$$V_{\mathrm{dd}} = \frac{\mu_0}{4\pi}\frac{\boldsymbol{\mu}\cdot\boldsymbol{\mu}' - 3(\boldsymbol{\mu}\cdot\hat{\boldsymbol{r}})(\boldsymbol{\mu}'\cdot\hat{\boldsymbol{r}})}{r^3}$$

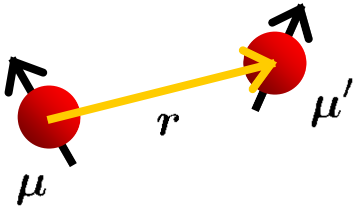


- anisotropic and long-range interaction



Magnetic Dipole-Dipole Interaction

$$V_{\mathrm{dd}} = \frac{\mu_0}{4\pi} \frac{\boldsymbol{\mu} \cdot \boldsymbol{\mu}' - 3(\boldsymbol{\mu} \cdot \hat{\boldsymbol{r}})(\boldsymbol{\mu}' \cdot \hat{\boldsymbol{r}})}{r^3}$$



- anisotropic and long-range interaction
  - phase shift for a scattering potential $\sim 1/r^n$

$$\delta_l = \begin{cases} k^{2l+1} & l < (n-3)/2 \\ k^{n-2} & \text{otherwise} \end{cases}$$

$n = 3$

$\Rightarrow \ \delta_l \sim k$

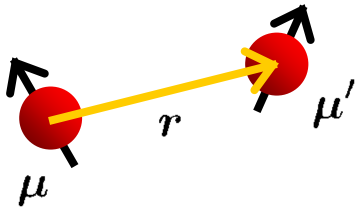
all partial-waves contribute to the scattering!

cf) van der Waals potential $\sim 1/r^6 \longrightarrow \delta_0 \sim k, \delta_{l\geq 1} \sim o(k)$

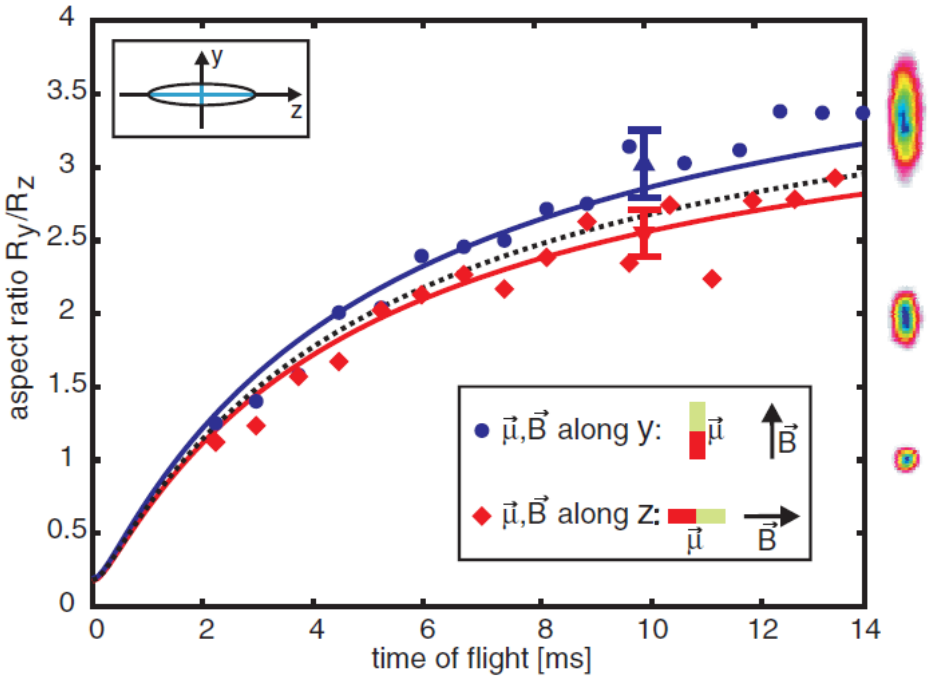
can be characterized with s-wave scattering length

Magnetic Dipole-Dipole Interaction

$$V_{\mathrm{dd}} = \frac{\mu_0}{4\pi}\frac{\boldsymbol{\mu}\cdot\boldsymbol{\mu}' - 3(\boldsymbol{\mu}\cdot\hat{\boldsymbol{r}})(\boldsymbol{\mu}'\cdot\hat{\boldsymbol{r}})}{r^3}$$



- anisotropic and long-range interaction



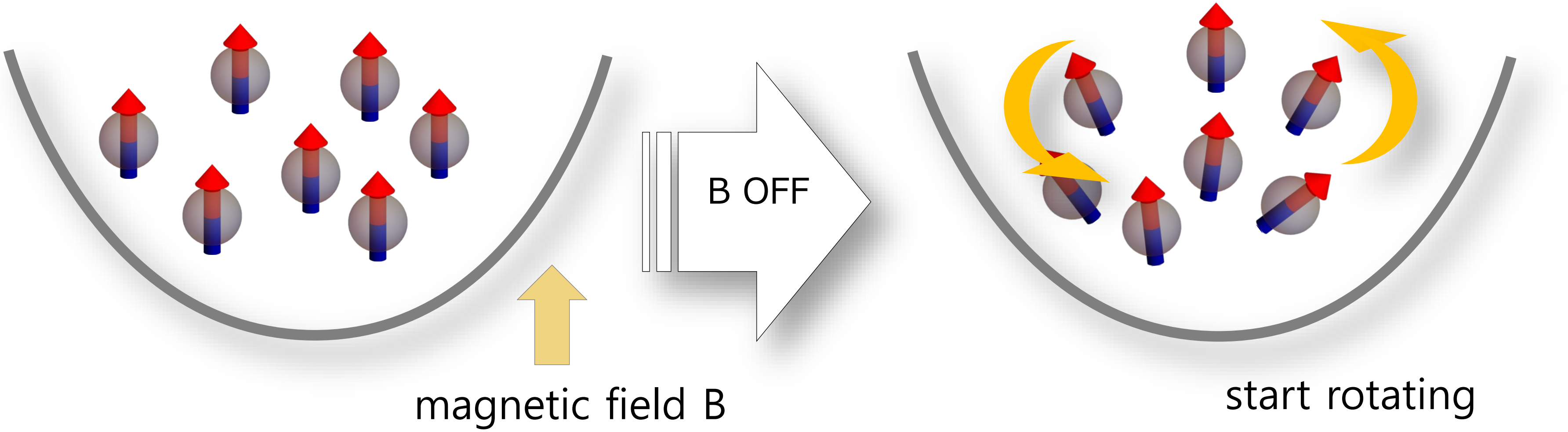
Anisotropic expansion of a spin-polarized gas

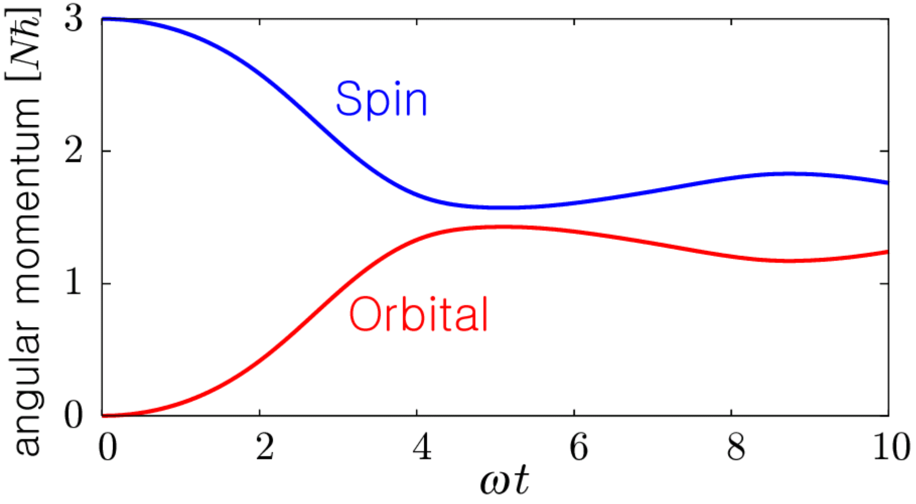
J. Stuhler, et al.,
PRL **95**, 150406 ('05)

➡ What happens when the system has spin degrees of freedom?

Einstein-de Haas Effect

YK, Saito, and Ueda, PRL **96**, 080405 ('06)
Santos & Pfau, PRL **96**, 190404 ('06)





Einstein-de Haas Effect

Einstein & de Haas (1915)

- magnetization = angular moment

The ferromagnet starts rotating
when the electric current of the coil is reversed

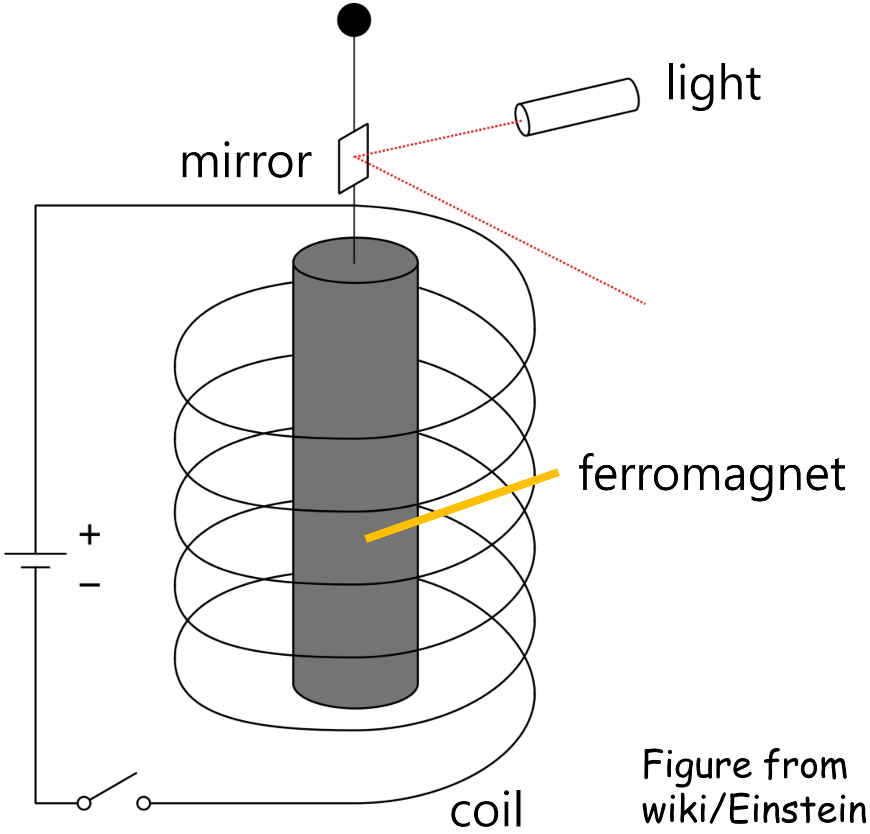
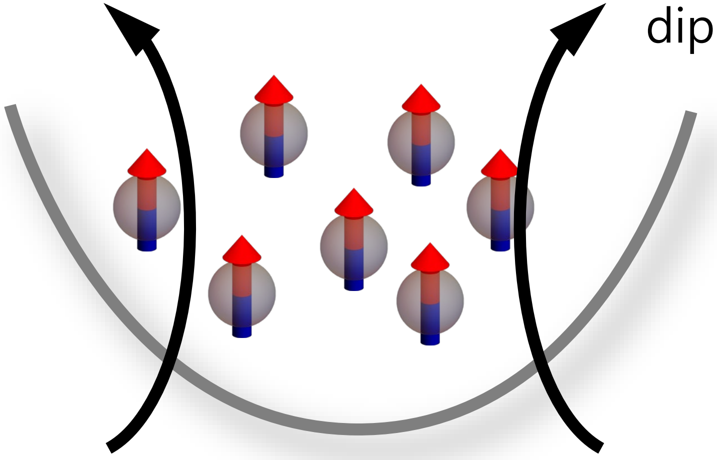


Figure from
wiki/Einstein de Haas

Einstein-de Haas Effect

YK, H. Saito, and M. Ueda, PRL **96**, 080405 ('06)

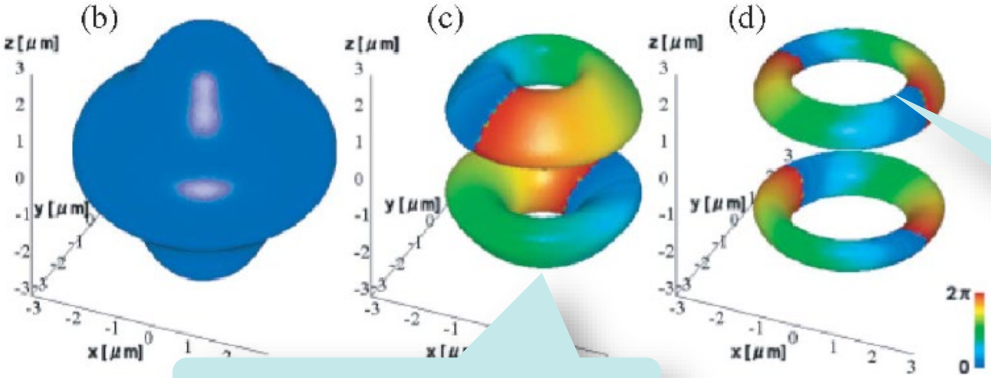


dipole field created by dipole moments in the BEC

➡ dipole moment of each atom undergoes Lamore precession about the dipole field

multicomponent macroscopic wave function

$|m_S = -S\rangle$ $|m_S = -S+1\rangle$ $|m_S = -S+2\rangle$



…

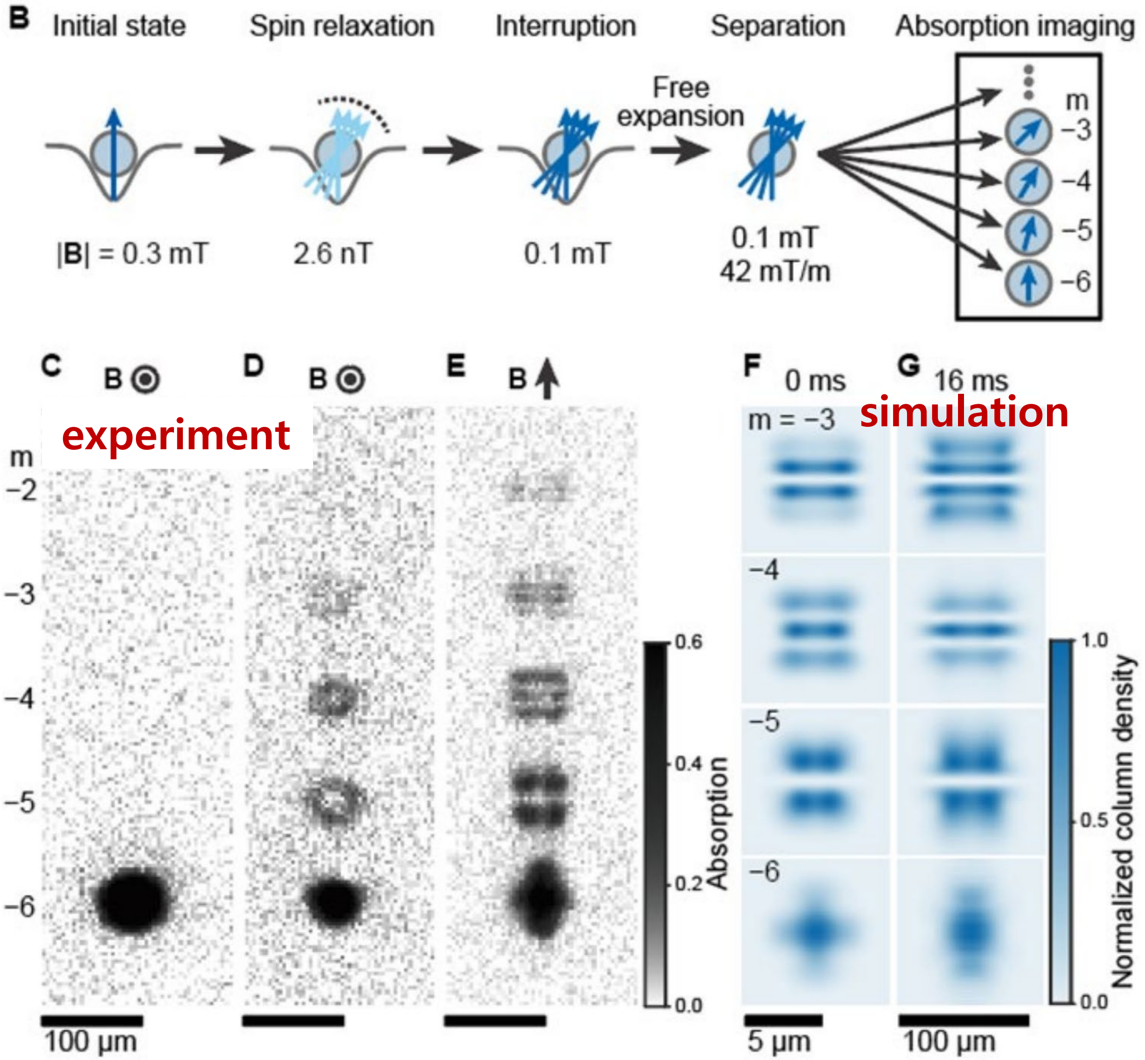
vortex: winding -2

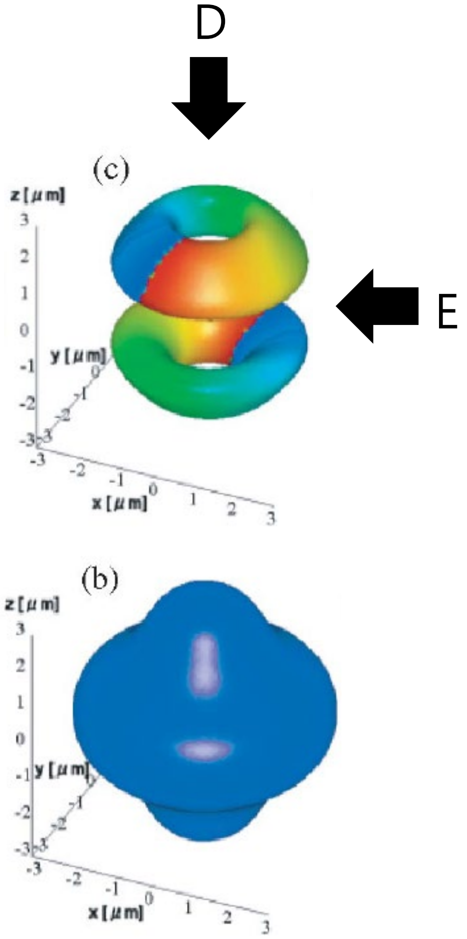
vortex: winding -1

Experimental observation of EdH Effect

- Europium atom with $7\mu_B$, S=6

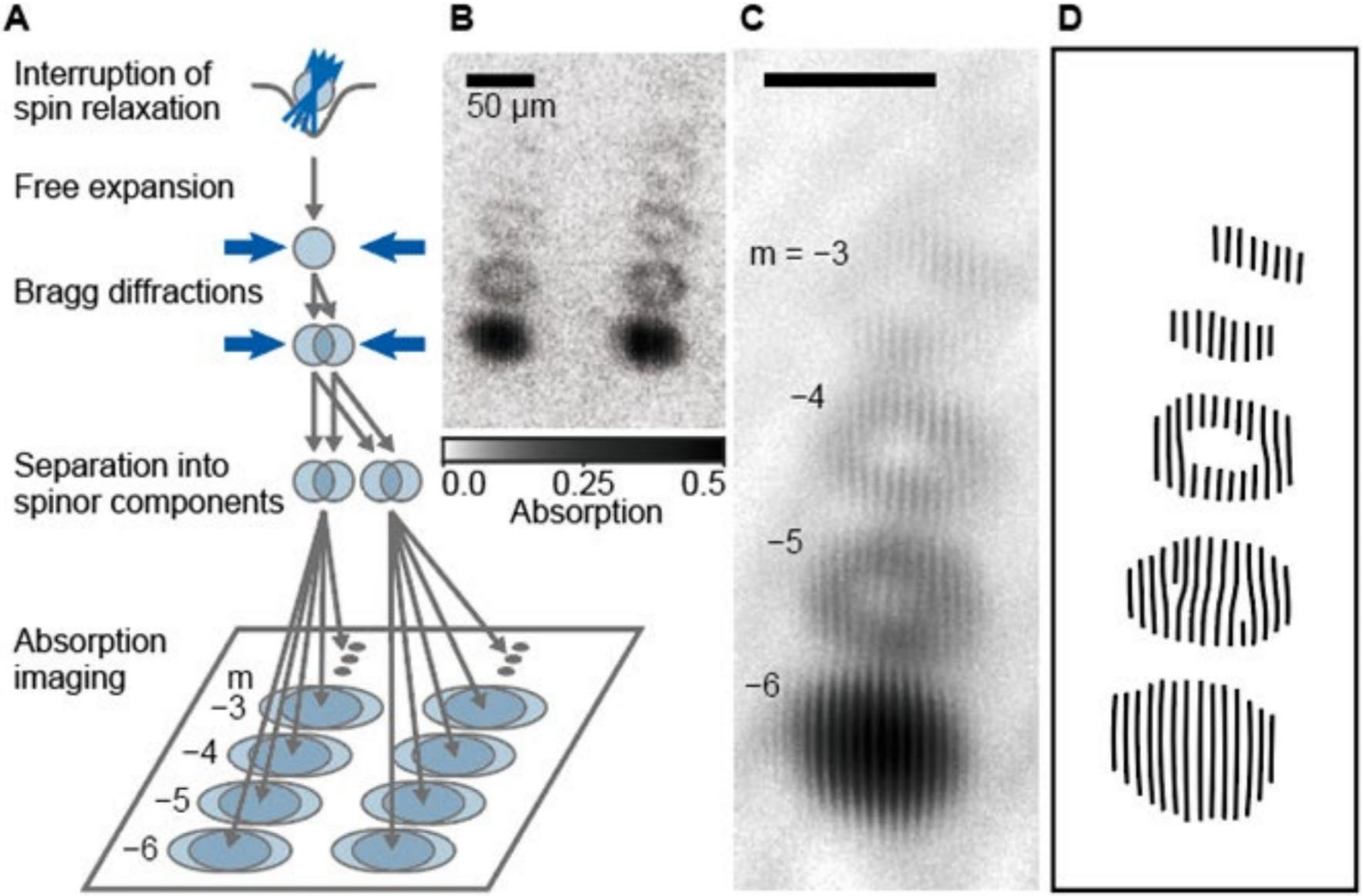
H. Matsui et al., arXiv:2504.17357





Observation of Phase Winding

H. Matsui et al., arXiv:2504.17357



averaged image of 116 iterations

Acknowledgements

Various studies on cold atomic gases
including topological excitations, dipolar gases,
non-equilibrium spin dynamics, spin-orbit coupled systems

THEORY

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Yuki Miyazawa (Inst. of Science Tokyo)

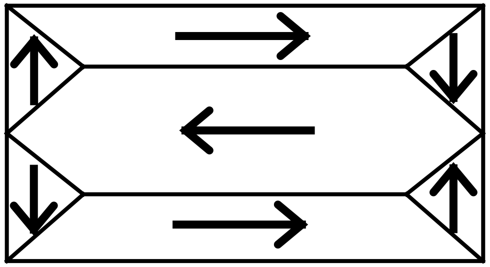
Review on spinor BECs

YK & Ueda, Physics Reports **520**, 253 ('12)

Appendix

Stable Spin Configuration under MDDI

- Flux-closure structure in ferromagnets $\nabla \cdot \boldsymbol{M} = 0$



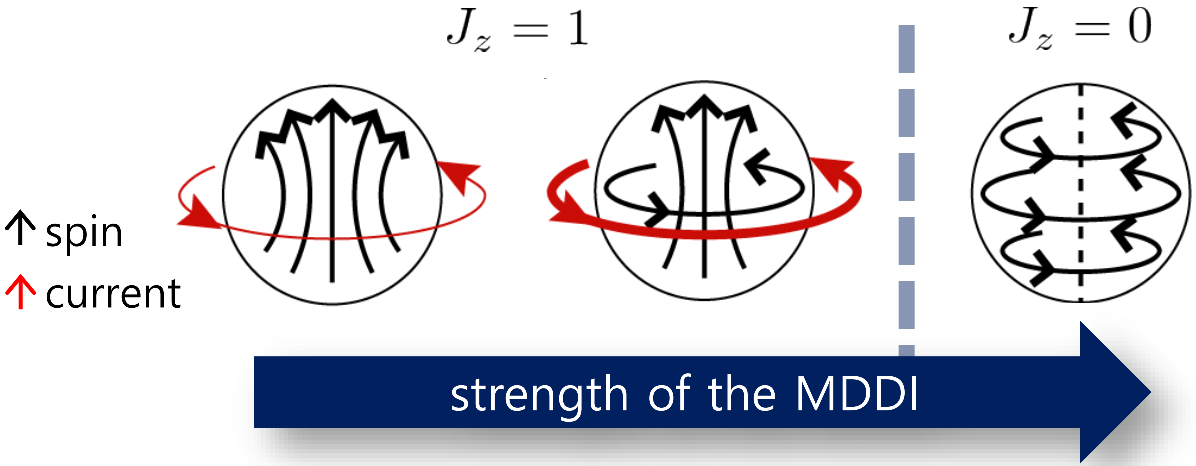
Landau & Lifshitz (1935)

- Eigenstate of $J_z = F_z + L_z$

$$\psi_m(r, \varphi, z) = e^{i(J_z - m)\varphi} f_m(r, z)$$

mixing of different m results in spin vortex state

- ground-state spin texture in a spin-1 ferromagnetic BEC at B=0



YK, Saito & Ueda,
PRL **97**, 130404 ('06)