

Exploring collective phenomena in

ultracold Bose-Einstein condensates

made of magnetic atoms



Daniel Petter



Dipolar Quantum Gases group Supervised by Univ.-Prof. Francesca Ferlaino

8. Jan. 2020, MIP Seminar



How do two magnets interact?





Youtube: Science Bits

INTRODUCTION - MAGNETISM





INTRODUCTION - MAGNETISM





INTRODUCTION - MAGNETISM



actinium

thorium

232.0

protactinium

231.0

uranium

238.0

neptunium

plutonium

americium

curium

berkelium

californium

einsteinium

fermium

mendelevium

nobelium

lawrencium

1																	18	
1																	2]
н																	He	
hydrogen	2											12	14	15	16	17	helium	
[1.007; 1.009]	2	1										13	14	15	10	17	4.003	-
3												D D	Ô		Å	9	10	
LI	Be											B	C	N	O	F	Ne	
[6.938; 6.997]	9.012											[10.80; 10.83]	[12.00; 12.02]	[14.00; 14.01]	[15.99; 16.00]	19.00	20.18	
11	12	1										13	14	15	16	17	18	1
Na	Ma											Δι	Si	Р	S	CI	Δr	
sodium	magnesium			_		_						aluminium	silicon	phosphorus	sulfur	chlorine	argon	
22.99	24.31	3	4	5	6	7	8	9	10	11	12	26.98	[28.08; 28.09]	30.97	[32.05; 32.08]	[35.44; 35.46]	39.95	_
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
Κ	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
potassium	calcium	scandium	titanium	vanadium	chromium	manganese	iron	cobalt	nickel	copper	zinc	gallium	germanium	arsenic	selenium	bromine	krypton	
38.10	38	30	47.87	<u> </u>	12.00	13	11	45	46	47	18	AQ	50	51	52	53	54	1
Dh	°.	v	7-	NIL	Mo	Ta	D	Dh	Da	۸~	60	40	6.	Ch.	Ta		V.	
KD	SI	Vttrium	Zirconium	niohium	molyhdenum	I C technetium	KU ruthenium	rhodium	PU	Ag	cadmium	indium	JII	3D antimony	tellurium	iodine	xenon	
85.47	87.62	88.91	91.22	92.91	95.96(2)	teennedam	101.1	102.9	106.4	107.9	112.4	114.8	118.7	121.8	127.6	126.9	131.3	
55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	1
Cs	Ba	lanthanoids	Hf	Та	W	Re	Os	lr	Pt	Au	Hq	TI	Pb	Bi	Po	At	Rn	
caesium	barium		hafnium	tantalum	tungsten	rhenium	osmium	iridium	platinum	gold	mercury	thallium	lead	bismuth	polonium	astatine	radon	
132.9	137.3		178.5	180.9	183.8	186.2	190.2	192.2	195.1	197.0	200.6	[204.3; 204.4]	207.2	209.0		Ļ		
87	88	89-103	104	105	106	107	108	109	110	111	112		114		116			
Fr	Ra	actinoids	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn		FI		LV			
francium	radium		rutherfordium	dubnium	seaborgium	bohrium	hassium	meitnerium	darmstadtium	roentgenium	copernicium		flerovium		livermorium			
																l.		
										arhium								
		57	58	59	60	61	62	63	64	65	ervi	um	68	69	70	71		
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb		по	Er	Tm	Yb	Lu		
		lanthanum	cerium	praseodymium	neodymium	promethium	samarium	europium	gadolinium	terbium	dysprosium	holmium	erbium	thulium	ytterbium	lutetium		
		138.9	140.1	140.9	144.2		150.4	152.0	157.3	158.9	102.0	104.9	107.3	108.9	1/3.1	1/5.0		
		89	90	91	92	93	94	95	96	97	98	99	100	101	102	103		
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

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ENTERING THE QUANTUM WORLD WITH MAGNETIC ERBIUM ATOMS



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1 -0 0 -0 -0	$1 \mu_B$																	18
Normalized biological	1 H hydrogen	~0 u	lo.													~	0 μ _B	2 He
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Ng sodum 22.86 Mg may signal Sich suffur series F Sich suffur pale; zion Sich prospino suffur pale; zion P Sich suffur pale; zion Sich suffur pale; zion P Sich suffur pale; zion Sich prospino suffur pale; zion P Sich suffur pale; zion Cl suffur pale; zion Arr prospino suffur pale; zion 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 85 Se selecian 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 85 85 101 47.27 78 78 65 65.47 48 49 50 51 52 53 54 Rb 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54	11	12											13	14	15	16	17	18
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K Ca polesum state Sc cardum state Ti itanium search state V Cr chronium sagenese state Mn sagenese state Fe ton state Co coper state Zn coper state Ga state	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
310 40.06 44.46 47.87 50.94 82.00 64.44 56.85 68.86 66.367 66.872 72.253 74.827 79.86(3) 79.00 88.89 37 38 39 40 41 42 43 44 45 46 47 48.8 49 50 51 52 53 54 Rb Y Zr Nb Nb Nb Nb Tc Ru Rh Pd Agg Cd antimony tituinitian tin sinitian tin sinitian tin tin <thtin< th=""> tin tin</thtin<>	K potassium	Ca calcium	Sc scandium	Ti titanium	V vanadium	Cr chromium	Mn manganese	Fe	Co cobalt	Ni nickel	Cu	Zn zinc	Ga gallium	Ge germanium	As arsenic	Se selenium	Br bromine	Kr krypton
3/2 3/3 4/3 4/4 4/3 4/4	39.10	40.08	44.96	47.87	50.94	52.00	54.94	55.85	58.93	58.69	63.55	65.38(2)	69.72	72.63	74.92	78.96(3)	79.90	83.80
Nationalization Sint standium serve Year of the serve serve Zin serve serve Numerican serve <	Dh	30 Cr	39 V	40 7r	41 Nh	42 Mo	43 To	44 D.1	40 Dh	40 Dd	47 A a	40 Cd	49 Im	00 6 m	SI Ch	52 T o	53	54 V o
85.47 87.2 98.21 91.22 92.91 95.96(2) 101.1 102.9 108.4 107.9 112.4 114.8 118.7 12.8 127.8 128.9 131.3 55 56 57.71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 Cessum 137.9 137.9 80 81 82 83 84 85 86 687 68 89-103 104 105 106 107 108 109 110 111 112 114 114 114 116 115 116 116 117 108 109 110 111 112 114 114 116 115 116 <th>rubidium</th> <th>strontium</th> <th>yttrium</th> <th>zirconium</th> <th>niobium</th> <th>molybdenum</th> <th>technetium</th> <th>ruthenium</th> <th>rhodium</th> <th>palladium</th> <th>silver</th> <th>cadmium</th> <th>indium</th> <th>tin</th> <th>antimony</th> <th>tellurium</th> <th>iodine</th> <th>xenon</th>	rubidium	strontium	yttrium	zirconium	niobium	molybdenum	technetium	ruthenium	rhodium	palladium	silver	cadmium	indium	tin	antimony	tellurium	iodine	xenon
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87 Fr 88 radium 89-103 actinoids 104 Rf 105 Db dubnium 106 Sg seaborgium 107 Bh bohrium 108 Hs hassium 109 Mt metherium 110 Ds darmstadium 111 Rg roentgenium 112 Cn copernicum 114 Fl Cn copernicum 114 Fl ferovium 116 Lv ivermorium V V V Sg seaborgium 106 107 108 109 110 111 112 Cn copernicum 114 Fl flerovium 116 Lv ivermorium V	132.9	137.3		178.5	180.9	183.8	186.2	190.2	192.2	195.1	197.0	200.6	[204.3; 204.4]	207.2	209.0	polonium	ustuarie	Tudon
Fr franciumRa radiumactinoidsRf rutherfordiumDb dubniumSg seaborgiumBh bohriumHs hassiumMt metheriumDs darmstadtiumRg roentgeniumCn coperniciumFI teroviumLv livermorium75859606162636465666768697071La lanthanumCeium raseodymiumPr praseodymiumNd neodymiumPm promethiumSm isoEu ueropiumGd6465666768697071La lanthanumCeium raseodymiumPr praseodymiumNd portentiumPm promethiumSm isoEu ueropiumGd6465666768697071La lanthanumCeium raseodymiumPr praseodymium9394959697989910010110210389 actiniumPha rusiumPa rusiumNp rusiumPu plutoniumAm americumCm americumBk californiumFm californiumMd resideniumNo rusiumLr laverencium89 actinium90 rusium91 rusium92939495 rusium96 curiumPf Bk californiumBk californiumFm rusiumMd rusiumNo rusium89 rusium90 rusium91 rusiumNp rusiumNp rusiumPu rusium <t< th=""><th>87</th><th>88</th><th>89-103</th><th>104</th><th>105</th><th>106</th><th>107</th><th>108</th><th>109</th><th>110</th><th>111</th><th>112</th><th></th><th>114</th><th></th><th>116</th><th></th><th></th></t<>	87	88	89-103	104	105	106	107	108	109	110	111	112		114		116		
57 58 59 60 61 62 63 64 65 Dy terbium 66 67 68 69 70 71 Lu 138.9 140.1 120.9 144.2 160.4 152.0 157.3 158.9 159.9 60 67 68 69 70 71 Lu 138.9 140.1 140.9 144.2 160.4 152.0 157.3 158.9 160 67 68 69 70 71 Lu 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 Ac Th protactinium 231.0 238.0 104 plutonium americium curium Bk 67 Bk Esinteinium fermium nobelium lawrencium	Fr francium	Ra radium	actinoids	Rf rutherfordium	Db dubnium	Sg seaborgium	Bh bohrium	HS hassium	Mt meitnerium	DS darmstadtium	Rg roentgenium	Cn copernicium		FI flerovium	1	LV livermorium		
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	I		10 μ _P											2012				
La Ianthanum 138.9Ce cerium 140.1Pr praseodymium 140.9Pm nomethium 144.2Sm samarium 150.4Eu europium 150.4Gd gadolinium 157.3Tb try try 157.3Dy tho thornium 152.9Ho thornium they thornium textTm thulium thulium thulium thulium 175.3Yb tur Itulium 175.3Lu lutetium 175.389 Ac actinium 232.091 protactinium 231.092 uranium 238.093 P4 P4 protactinium 238.096 P4 P4 plutonium plutonium americum plutonium americum96 Cm Cm Cm curium97 P8 P6 Cf californium californium einsteinium101 model mendelevium nobelium102 luto luto			57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	
Ianthanum 138.9cerium 140.1praseodymium 140.9neodymium 144.2promethium samarium 150.4samarium 150.4europium 150.0terbium 157.3terbium 162.5ebrium 162.5tholmium 162.5ebrium 161.9tholmium 187.3ebrium 188.9tholmium 187.3ebrium 188.9tholmium 187.3ebrium 188.9tholmium 182.5ebrium 180.9tholmium 187.3ebrium 180.9tholmium 180.9ebrium 180.9tholmium 180.9ebrium 180.9tholmium 180.9ebrium 180.9tholmium 180.9ebrium 180.9tholmium 180.9ebrium 180.9tholmium <th></th> <th></th> <th>La</th> <th>Ce</th> <th>Pr</th> <th>Nd</th> <th>Pm</th> <th>Sm</th> <th>Eu</th> <th>Gd</th> <th>Tb</th> <th>Dy</th> <th>Ho</th> <th>Er</th> <th>Tm</th> <th>Yb</th> <th>Lu</th> <th></th>			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
8990919293949596979899100101102103Ac actinium 232.0Th 231.0Pa 231.0U 231.0U 231.0Np 231.0Pu 231.0Pu plutonium 231.096 Pu plutonium97 Cm curium98 Bk curium99 Cf californium100 Es einsteinium101 Md mendelevium102 No nobelium103 Lr lawrencium			lanthanum 138.9	cerium 140.1	praseodymium 140.9	neodymium 144.2	promethium	samarium 150.4	europium 152.0	gadolinium 157.3	terbium 158.9	dysprosium 162.5	holmium 164.9	erbium 167.3	thulium 168.9	ytterbium 173.1	lutetium 175.0	
Ac actiniumTh thorium 232.0Pa protactinium 231.0U uranium 238.0Np neptuniumPu plutoniumAm americiumCm curiumBk berkeliumCf californiumEs einsteiniumFm mendeleviumMd nobeliumNo nobeliumLr lawrencium			89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	
			Ac actinium	Th thorium 232.0	Pa protactinium 231.0	U uranium 238.0	Np neptunium	Pu plutonium	Am americium	Cm curium	Bk berkelium	Cf californium	Es einsteinium	Fm fermium	Md mendelevium	No nobelium	Lr lawrencium	

magnetic moment: 7 μ_{B}





50 TIMES **STRONGER** MAGNETS THAN ALKALI ATOMS



EXPLORE NEW PHYSICS

Publications within this (upcoming) thesis:

• Quantum-Fluctuation-Driven Crossover from a Dilute Bose-Einstein Condensate to a Macrodroplet in a Dipolar Quantum Fluid

L. Chomaz, S. Baier, D. P., M. J. Mark, F. Wächtler, L. Santos, F. Ferlaino, PRX 6, 041039 (2016)

- Observation of roton mode population in a dipolar quantum gas

 L. Chomaz, R. v. Bijnen, <u>D. P.</u>, G. Faraoni, S. Baier, J. H. Becher, M. J. Mark, F. Waechtler, L. Santos, F. Ferlaino, Nat. Phys. 14, 442 (2018)
- Long-Lived and Transient Supersolid Behaviors in Dipolar Quantum Gases
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- Probing the Roton Excitation Spectrum of a stable dipolar Bose gas,
 <u>D. P.</u>, G. Natale, R. M. W. van Bijnen, A. Patscheider, M. J. Mark, L. Chomaz, F. Ferlaino, PRL **122**, 183401 (2019)



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What is an excitation spectrum (dispersion relation)?

Describes the energy E that is needed to excite a physical system at a certain momentum p (or velocity v)





m ... mass of atom

p = mv



At low momentum, atoms respond *collectively* (due to delocalisation + interactions)





At low momentum, atoms respond *collectively* (due to delocalisation + interactions)





Collective excitations travel as *plane waves* through BEC (similar to phonons in solids, or waves in water)



At low momentum, atoms respond *collectively* (due to delocalisation + interactions)







Bragg spectroscopy:

- Two laser beams cross under angle θ at atomic cloud
- Frequency difference ω
- Excitation via two-photon process





- Frequency difference ω
- Excitation via two-photon process





Excitation via two-photon process ٠

٠





Excitation via *two*–*photon process* ٠

٠

Momentum transfer **p** happens only when energy ($\hbar\omega$) ٠ matches excitation spectrum

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Implement a Bragg spectroscopy setup:

Main requirement:

Easy tunability over relevant momentum and energy range

Technical implementation with *digital micromirror device:*

- Use holographic gratings to create two Bragg beams from one incoming laser beam
- Allows to change momentum *p* and frequency ω independently via computer programm



Programmable mirror board with 1920x1080 tiny mirrors

mirror

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Implement a Bragg spectroscopy setup:

Main requirement:

Easy tunability over relevant momentum and energy range

Technical implementation with *digital micromirror device:*

- Use holographic gratings to create two Bragg beams from one incoming laser beam
- Allows to change momentum *p* and frequency ω independently via computer programm
- Reguirements: Additional Laser setup, Programming, offline calibration, implementation into experiment



Measurement sequence:

• Prepare cloud





Measurement sequence:

- Prepare cloud
- Apply a short Bragg pulse with fixed momentum
- Let atoms expand in free space (switch off trap)
- Take a picture





Measurement sequence:

- Prepare cloud
- Apply a short Bragg pulse with fixed momentum
- Let atoms expand in free space (switch off trap)
- Take a picture





Repeat for different momenta and compare to theory





What happens when the energy of the roton minimum is tuned to zero?









