

University of Connecticut



Workshop on Quantum Simulation/Computation with Cold Atoms and Molecules

> AMO Tutorial 2: cold atoms

> > by Robin Côté

Aspen, Wednesday June 3 2009

Outline



- Introduction/motivation
 - Property wish list
- Overview of AMO platforms
- Trapped ion / atom-ion systems
- Cold atoms
 - Rydberg atoms
- Cold molecules
- Other applications
- Concluding remarks



Cold Atoms

The list is growing

	GROUP		PF	RI	OD	OIC	TA	BL	E (DF	TH	E		M	EN'	ΓS			
	1 IA			2	27	27	//	http://www.ktf-split.hv/periodni/en/										18 VIIIA	
۵	1 1.0079			RELATIVE ATOMIC MASS (1)								7						2 4.0026	
21	Н						Metal Semimetal			Nonmetal								He	-
PE	HYDROGEN	2 114	GRO	UP IUPAC	3 1114	ROUPCAS		ali metal		tal UT Halogens element			13 1114	14 IVA	15 VA			HELIUM	
	3 6.941	4 9.0122	ATOMIC N	UMBER	10.811		Transition metals			a II8 Noble gas			5 10.811 6 12.011 7 14.007 8 15.999				9 18.998	10 20.180	
2	Li	Li Be			SYMBOL -B			Lanthanide			STANDARD STATE (25 °C: 101 kPa)			C	N	0	F	Ne	
<u></u>	LITHUM	REPVILIUM			BORON			Actinide	Ne - gas Fe - solid			(ra)	BORON	CARBON	NITROGEN	OXYGEN	ELLIOPINE	NEON	
	11 22.990	12 24.305			1		/ <u> </u>	- In	Ga	- liquid	To - synthe	lic	13 26,982	14 28.086	15 30.974	16 32.065	17 35.453	18 39.948	
3	Na	Μσ		ELE	MENT NAME				_	1	/		Al	Si	Р	S	CI	Ar	
	SODIUM	MAGNESIUM	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	- VIIIB -	10	11 18	12 IIB	ALUMINIUM	SILICON	PHOSPHORUS	SULPHUR	CHLORINE	ARGON	
	19 39.098	20 40.078	21 44.956	22 47.867	23 50.942	24 51.996	25 54.938	26 55.845	27 58.933	28 58.693	29 63.546	30 65.39	31 69.723	32 72.64	33 74.922	34 78.96	35 79.904	36 83.80	
- 4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
	POTASSIUM	CALCIUM	SCANDUIM	TITANILIM	VANADUIM	CHROMUM	MANGANESE	IRON	COBALT	NICKEI	COPPER	ZINC	GALLIM	GERMANIUM	ARSENIC	SELENIUM	BROMINE	KRYPTON	
	37 85.468	38 87.62	39 88.906	40 91.224	41 92.906	42 95.94	43 (98)	44 101.07	45 102.91	46 106.42	47 107.87	48 112.41	49 114.82	50 118.71	51 121.76	52 127.60	53 126.90	54 131.29	
5	Rh	Sr	v	7r	Nh	Mo	The	Ru	Rh	Pd	Δσ	Cd	In	Sn	Sh	Те	T	Xe	
	RUBIDIUM	STRONTIUM	YTTRIUM	ZIRCONIUM	NIOBILIM	MOLYBOENUM	TECHNETIUM	RUTHENUM	RHODIUM		SILVER	CADMILIM	INDIUM	TIN	ANTIMONY	TELLIRUM		XENON	
	55 132.91	56 137.33	57-71	72 178.49	73 180.95	74 183.84	75 186.21	76 190.23	77 192.22	78 195.08	79 196.97	80 200.59	81 204.38	82 207.2	83 208.98	84 (209)	85 (210)	86 (222)	
.6	Ce	Ra	La-Lu	Hf	Та	W	Re	Os	Ir	Pt	An	Ησ	TI	Ph	Ri	Po	At	Rn	
	CAESHIM	DADIUM	Lanthanide		TANTALIBA	TUNCSTEN	DHENHIM	OSMUM	IRIDIUM	DIATINUM	au	MEDCUPY	THALLING	LEAD	DISMUTH	POLONIUM	ASTATIME	PADON	1
·	87 (223)	88 (226)	89-103	104 (261)	105 (262)	106 (266)	107 (264)	108 (277)	109 (268)	110 (281)	111 (272)	112 (285)	TINELION	114 (289)	SIGMOTH	7 OLONIOM	ASTATIST	1012011	1
7	Fr	Ra	Ac-Lr	ngr	IDIh	Sa	TRIh	THIC	MIA	11 มีมากก	TInnn	Tunh		TImm					
	E PANCILIM	RADIUM	Actinide		DURNIUM	N SEABORCHIM	ROHBITIM	TUTO	TATIC		O di di			() and					
				LANTHAN	DE											Copyright © 19	oyright © 1998-2003 EniG. (eni@ktf-split.hr)		
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001) Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets			83 (2001) with five	57 138.91	58 140.12	59 140.91	60 144.24	61 (145)	62 150.36	63 151.96	64 157.25	65 158.93	66 162.50	67 164.93	68 167.26	69 168.93	70 173.04	71 174.97	
			La	Ce	Pr	Nd	IPm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
indicates the mass number of the longest-lived isotope of the element.				LANTHANUM	CERIUM	PRASECOYMIUM	NEODYMIUM	PROMETHIUM	SAMARIUM	EUROPIUM	GADOLINIUM	TERBIUM	DYSPROSIUM	HOLMIUM	ERBIUM	THULIUM	YTTERBIUM	LUTETIUM	
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.			ACTINIDE											i					
			89 (227)	90 232.04	91 231.04	92 238.03	93 (237)	94 (244)	95 (243)	96 (247)	97 (247)	98 (251)	99 (252)	100 (257)	101 (258)	102 (259)	103 (262)		
				Ac	Th	Pa	U	Np	1Pm	Am	Cm	BBK	Cf	lEs	Fin	M[d]	NO	llr	
Edit	or Aditus Vardh	an lariwar Rent	linx com)	ACTINIUM	THORIUM	PROTACTINIUM	URANIUM	NEPTUNIUM	PLUTONIUM	AMERICIUM	CURIUM	BERKELIUM	CALIFORNIUM	EINSTEINIUM	FERMIUM	MENDELEVIUM	NOBELIUM	LAWRENCIUM	

-2-level cycling transitions

-available transitions

Quantum computer wish list

- Stable trapping/storage
- Addressable qubits
- Gates between (separated) qubits
- Long coherence-, short interaction-times
- Scalability
- Strong, switchable interaction
- Readout/initialization

Collisional gate

- Phase gate
 - Each site initially in superposition of |0> and |1>
 - $$\begin{split} |A\rangle &\sim |0\rangle_A + |1\rangle_A & \text{b} \\ |B\rangle &\sim |0\rangle_B + |1\rangle_B & \\ |Q\rangle &\sim |00\rangle + |01\rangle + |10\rangle + |11\rangle \end{split}$$



- b) $|a\rangle |b\rangle |a\rangle |b\rangle$
- Change the trap for state $|1\rangle$
 - Collision induce a phase

 $|Q\rangle \sim |00\rangle + |01\rangle + |10\rangle + e^{i\phi}|11\rangle$

• $\phi = \pi$: phase gate $|Q\rangle \sim |00\rangle + |01\rangle + |10\rangle - |11\rangle$ Cirac-Zoller, PRA 61, 022304 (2000)

Using a mixture



Rydberg Atoms

- Alkali atoms are good candidates to encode qubits:
 - Measurement high quantum efficiency: e.g., cycling transition.
 - Easy cooling and trapping
 - Low decoherence times.
- Rydberg atoms resemble hydrogen atom:
 - Radius and dipole moment scale as n^2
 - Energy $\propto 1/(n-\delta_{n,\ell})^2$, quantum defect $\delta_{n,\ell}$
- Long lifetimes $\propto n^3$. 50p, τ =238 μ s (τ =.02 μ s for 5p)
- Large polarizability $\propto n^7$: Stark mixing other ℓ by electric fields \mathcal{F}

$$|49p\rangle = \alpha |49p\rangle + \beta |49s\rangle + \dots \text{ with } \beta = 0.11 \mathcal{F} \Rightarrow \widetilde{\mu}_{pp} = 2\alpha \beta \mu_{sp}$$
$$\mathcal{F} \uparrow \overrightarrow{\mu}_{A} \stackrel{\theta}{\longrightarrow} \overrightarrow{\mu}_{B} \qquad V_{d-d} = \frac{\overrightarrow{\mu}_{A} \cdot \overrightarrow{\mu}_{B}}{r^{3}} - 3 \frac{(\overrightarrow{r} \cdot \overrightarrow{\mu}_{A})(\overrightarrow{r} \cdot \overrightarrow{\mu}_{B})}{r^{5}}$$



Long-range wells



- Combination of coefficients can lead to long-range wells
 - "stable" if electron wave functions do not overlap (non-shaded region)
 - very extended molecules (few μm or more) : macrodimers
 - shallow wells can exist only in ultracold regime

 $in=70: D_e \sim 300 \text{ kHz}$ and $R_e \sim 100,000 a_0$ (100 levels spaced by a few kHz)

C. Boisseau, I. Simbotin, & R. Côté, PRL 88, 133004 (2002)

Mixed states

- When $\left|\frac{C_6}{R^6}\right| \sim \Delta E$, need to include couplings between states splitted by ΔE at $R \rightarrow \infty$
- Simple treatment with *np+np* and *ns+n*'s asymptotes
 - E.g., atomic states for 70p+70p and 70s+71s mix
 - Asymptotic form of electronic wave functions of atom pairs $|pp(1)\rangle$, $|pp(2)\rangle$ and $|ss'\rangle$ contain dipole-dipole terms
 - Need to diagonalize interactions (with correct symmetries and dipole moments) $$_{\!\scriptscriptstyle A}$ 2$

$$\begin{pmatrix} 0 & 0 & AR^{-3} \\ 0 & 0 & BR^{-3} \\ AR^{-3} & BR^{-3} & \Delta E \end{pmatrix} \qquad \begin{array}{c} A = \frac{-3}{3} \mu_{ps} \mu_{ps'} \\ B = \frac{4}{3\sqrt{2}} \mu_{ps} \mu_{ps'} \\ \Delta E \sim 213 \text{ MHz} \end{array}$$

K. Singer, J. Stanojevic, M. Weidemüller, and R. Côté, J. Phys. B 38, S295 (2005).

Coupled potential curves



Application: Phase Gate

"Simple" phase control gate
use atoms in an optical lattice
state prepared by Raman pulses

 $| \mathbf{A} \rangle = \frac{1}{\sqrt{2}} \left\{ | \mathbf{0} \rangle + | \mathbf{1} \rangle \right\}$ $| \mathbf{B} \rangle = \frac{1}{\sqrt{2}} \left\{ | \mathbf{0} \rangle + | \mathbf{1} \rangle \right\}$

• Two-qubit state

 $|\mathbf{Q}\rangle \neq |\mathbf{A}\rangle \otimes |\mathbf{B}\rangle$

 $|\mathbf{Q}\rangle = |\mathbf{00}\rangle + |\mathbf{01}\rangle + |\mathbf{10}\rangle - |\mathbf{11}\rangle$

• Possible also with excitation blockade

- strong dipole-dipole interactions
- degenerate states split
- laser pulse sequence gives a phase gate

D. Jaksch et al., PRL 85, 2208 (2000).





Application: Excitation Blockade

- van der Waals $\propto n^{11}$
 - interactions shift the two-photon resonance
- Low n or densities
 - Weak interactions between Rydberg atoms
 - 2-photon resonance is shifted at "small" *R*
 - below R_D, excitation of 2
 Rydberg atoms (or more)
 is prohibited
 - Isolated atom behavior



Separation R

- large n or densities
 - strong molecular interactions
 - resonance shifted at large R
 - Blockaded behavior

A sketch



Blockade & gates

- Ensemble of atoms
 - few μ m in size
 - 10-100 atoms



- Collective states
 - g \rangle : All atoms in ground state.
 - $|q^n\rangle$: Collective state of n-atoms in q.
 - $|r^1\rangle$: Only one excitation allowed in *r*.
- Prepare initial state
 - $|g\rangle \stackrel{\Omega\sqrt{N}}{\twoheadrightarrow} |r^1\rangle \stackrel{\Omega_q}{\twoheadrightarrow} |q^1\rangle$
 - Based on conditional excitation
 - Ensemble behaves as a "super-atom"

M.D. Lukin, M. Fleischhauer, R. Côté, L.M. Duan, D. Jaksch, J.I. Cirac, and P. Zoller, PRL **87**, 037901 (2001)

• Single-atom levels:



Gate using Blockade

• If sites individually addressable and shift large



D. Jaksch et al., PRL 85, 2208 (2000).

Observation with 2 atoms



E. Urban et al., Nature Phys. (2009).

Results

If control is excited (n=79)

- Lower probability of exciting the target



E. Urban et al., Nature Phys. (2009).

Many-body excitation

• When 2 atoms are excited in $58d_{3/2}$ – Rabi frequency is $\sqrt{2} \Omega$



A. Gaëtan et al., Nature Phys. (2009).

About a larger sample ?

low n or densities



Measurements

Excitation blockade:



- Many-body oscillation
 - difficult in large sample
 - Pfau in Rb BEC
 - n=90, 70 atoms, 10¹¹
 cm³, τ = 10 ns



- D. Tong *et al.*, PRL **93**, 063001 (2004).K. Singer, *et al.*, PRL **93**, 163001 (2004).
- Dipole blockade
 - observed by Pillet

Results from simulations

Large sample: 70 atoms and up to 7 excitations



Many-body treatment

Hamiltonian with 2-level atom i



 $f(t) = e^{-t^2/\sigma^2 - i\beta t^2}$

With definitions

$$\hat{\sigma}_{eg}^{i} \equiv |e_{i}\rangle \langle g_{i}|$$
$$\kappa_{ij} = \frac{C_{6}}{R_{ij}^{6}}$$

Simplification

• Equation of motion for σ -operators

where

Removing the Δ term using new scaled variables

$$\begin{split} &\tau = t/\sigma \quad , \quad \omega = \Omega\sigma \quad , \quad k_{ij} = \kappa_{ij}\sigma \quad , \quad \delta = \Delta\sigma \\ &\frac{d\hat{\sigma}_{ee}^{i}}{d\tau} = i\frac{\omega}{2} \left[g(\tau)\hat{\sigma}_{eg}^{i} - g^{*}(\tau)\hat{\sigma}_{ge}^{i} \right] \\ &\frac{d\hat{\sigma}_{eg}^{i}}{d\tau} = i\frac{\omega}{2}g^{*}(\tau) \left[2\hat{\sigma}_{ee}^{i} - 1 \right] + i\sum_{j\neq i}k_{ij}\hat{\sigma}_{eg}^{i}\hat{\sigma}_{ee}^{j} \\ &\text{where} \qquad g(\tau) = f(\tau)e^{i\delta\tau} \end{split}$$

Time dependence



Stronger interactions

- Time-dependent with n=90
 - 70 atoms
 - $-\rho = 10^{11} \text{ cm}^{-3}$
 - $-\tau = 10 \text{ ns}$ - Square pulse
 - V~(8 μm)³



Other studies

- Quantum random walk
 - Diffusion of excitation
 - Prepare using blockade
 - Freiburg and Dresden
- Superradiance



T. Wang et al., PRA 75, 033802 (2007).



Other applications

- Exotic many-body spin systems
 - Kitaev toric code



P. Zoller, talk at NSF sponsored workshop (April 2009).

PA in Rydberg gases



Potential wells

• s+s' & p+p' mixing \Rightarrow wells at shorter separation – "macrodimers" (ex., n=70 \Rightarrow R_e = 103 000 a.u.)



Separation R (x 10⁴ a.u.)

Application: Rydberg Molecules

- "Common" case
 - Tight molecular ion core
 - Loosely bound electron
- Interested in excited molecules with large internuclear separation R
- Giant Helium dimers produced by He(2³S↑)+He(2³P↑)
 - *R* ~ 150 1150 *a*₀ and binding energy 1-2 GHz
 [Leonard *et al.*, Phys. Rev. Lett. **91**, 073203 (2003)]
- Trilobite or butterfly states (Greene et al.)
 - One atom excited and one in ground state
 - Electron scatters from neutral ground atom
 - Binding energies ~ 2GHz at n=70
 - **Fypical** R_e : 500 a_0
- Borromean states (J.M. Rost)











Recent measurements

- Density function for 5s-35s
 - Bound levels observed
 - ♦ R~1900 a.u.
 - v=0 at -23.4 MHz



T. Pfau's group, in Nature (2009).

Quick break

• To refresh yourself

