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# 离子阱物理简介 **II**

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**Spin.ustc.edu.cn**

**2020/10**

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# 内容

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背景介绍

自组织的离子链

光与离子的相互作用

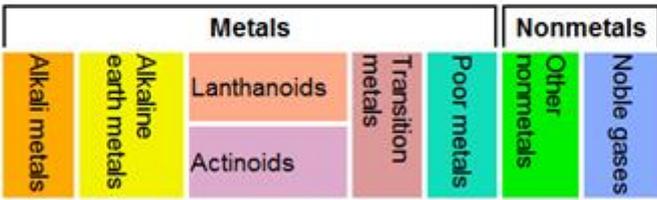
量子计算和量子模拟

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# Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 <b>H</b> Hydrogen 1.00794	2 <b>He</b> Helium 4.002602																
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012182																
11 <b>Na</b> Sodium 22.98976928	12 <b>Mg</b> Magnesium 24.3050																
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.955912	22 <b>Ti</b> Titanium 47.867	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938045	26 <b>Fe</b> Iron 55.845	27 <b>Co</b> Cobalt 58.933195	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.38	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92160	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.796
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.96	43 <b>Tc</b> Technetium (97.9072)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.90550	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.710	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.293
55 <b>Cs</b> Caesium 132.9054519	56 <b>Ba</b> Barium 137.327	57-71	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.94788	74 <b>W</b> Tungsten 183.84	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.217	78 <b>Pt</b> Platinum 195.084	79 <b>Au</b> Gold 196.966569	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98040	84 <b>Po</b> Polonium (209.9824)	85 <b>At</b> Astatine (208.9871)	86 <b>Rn</b> Radon (222.0176)
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium (226)	89-103	104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (266)	107 <b>Bh</b> Bohrium (264)	108 <b>Hs</b> Hassium (277)	109 <b>Mt</b> Meitnerium (268)	110 <b>Ds</b> Darmstadtium (271)	111 <b>Rg</b> Roentgenium (272)	112 <b>Uub</b> Ununbium (285)	113 <b>Uut</b> Ununtrium (284)	114 <b>Uuq</b> Ununquadium (289)	115 <b>Uup</b> Ununpentium (288)	116 <b>Uuh</b> Ununhexium (292)	117 <b>Uus</b> Ununseptium (289)	118 <b>Uuo</b> Ununoctium (294)

- C** Solid
- Hg** Liquid
- H** Gas
- Rf** Unknown



For elements in the s and p blocks, the number of valence electrons is equal to the group number. For elements in the d and f blocks, the number of valence electrons is equal to the group number minus 10. Elements with the longest half-life is in parentheses.

常用为单个价电子离子

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57 <b>La</b> Lanthanum 138.90547	58 <b>Ce</b> Cerium 140.118	59 <b>Pr</b> Praseodymium 140.90768	60 <b>Nd</b> Neodymium 144.242	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92535	66 <b>Dy</b> Dysprosium 162.500	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.054	71 <b>Lu</b> Lutetium 174.9668
89 <b>Ac</b> Actinium (227)	90 <b>Th</b> Thorium 232.03806	91 <b>Pa</b> Protactinium 231.03688	92 <b>U</b> Uranium 238.02891	93 <b>Np</b> Neptunium (237)	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (262)



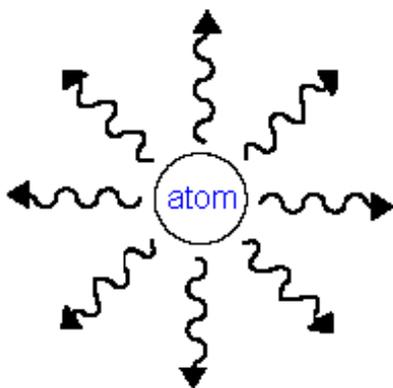
# 激光冷却-多普勒-失谐

Absorption of N photons

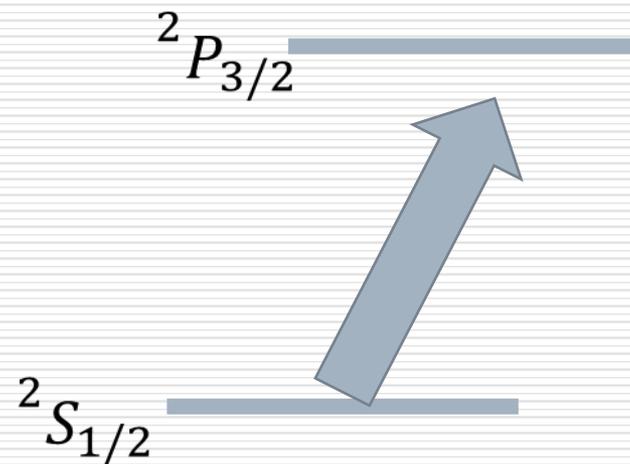


$$\Delta \vec{p} = N \hbar k \hat{z}$$

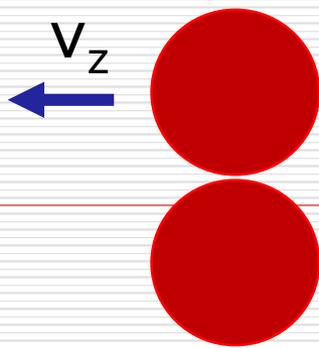
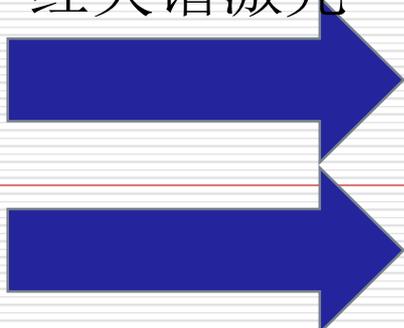
Emission of N photons



$$\langle \Delta \vec{p} \rangle = 0$$



红失谐激光

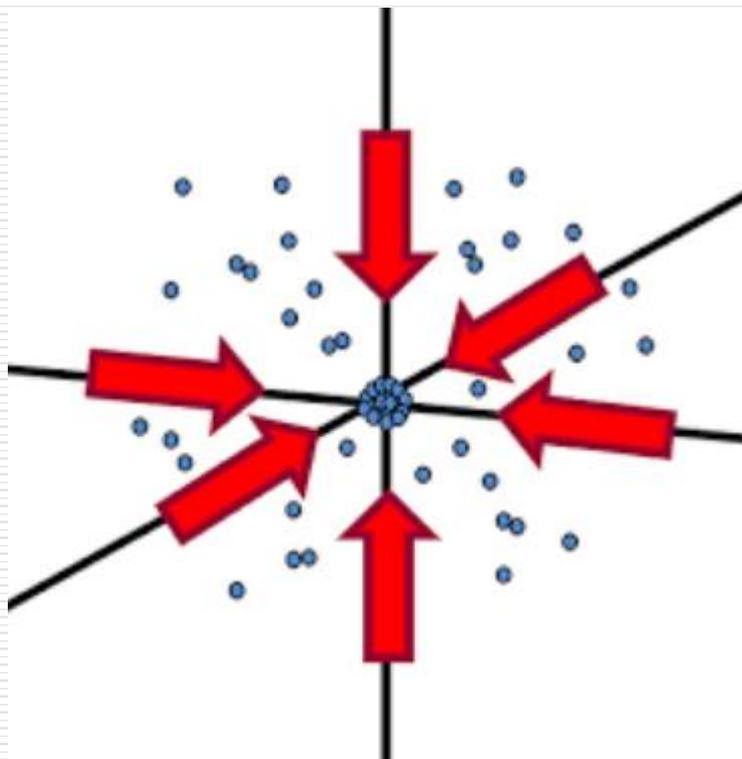


多普勒移动，更接近共振，吸收动量

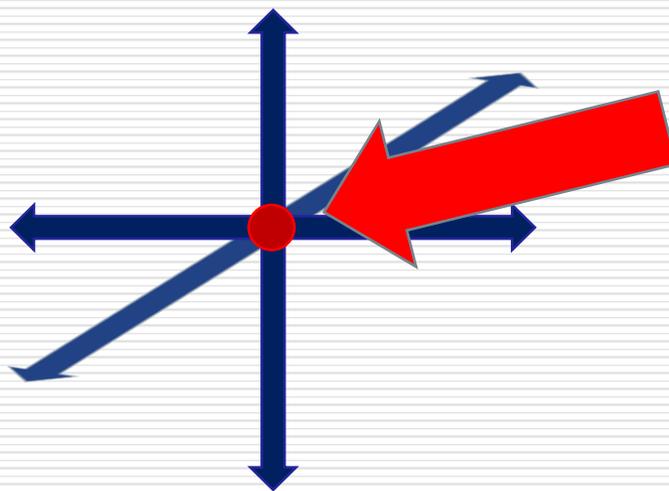
更远离共振，散射较弱

# 激光冷却-多普勒

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非约束原子，三维冷却，  
六束激光



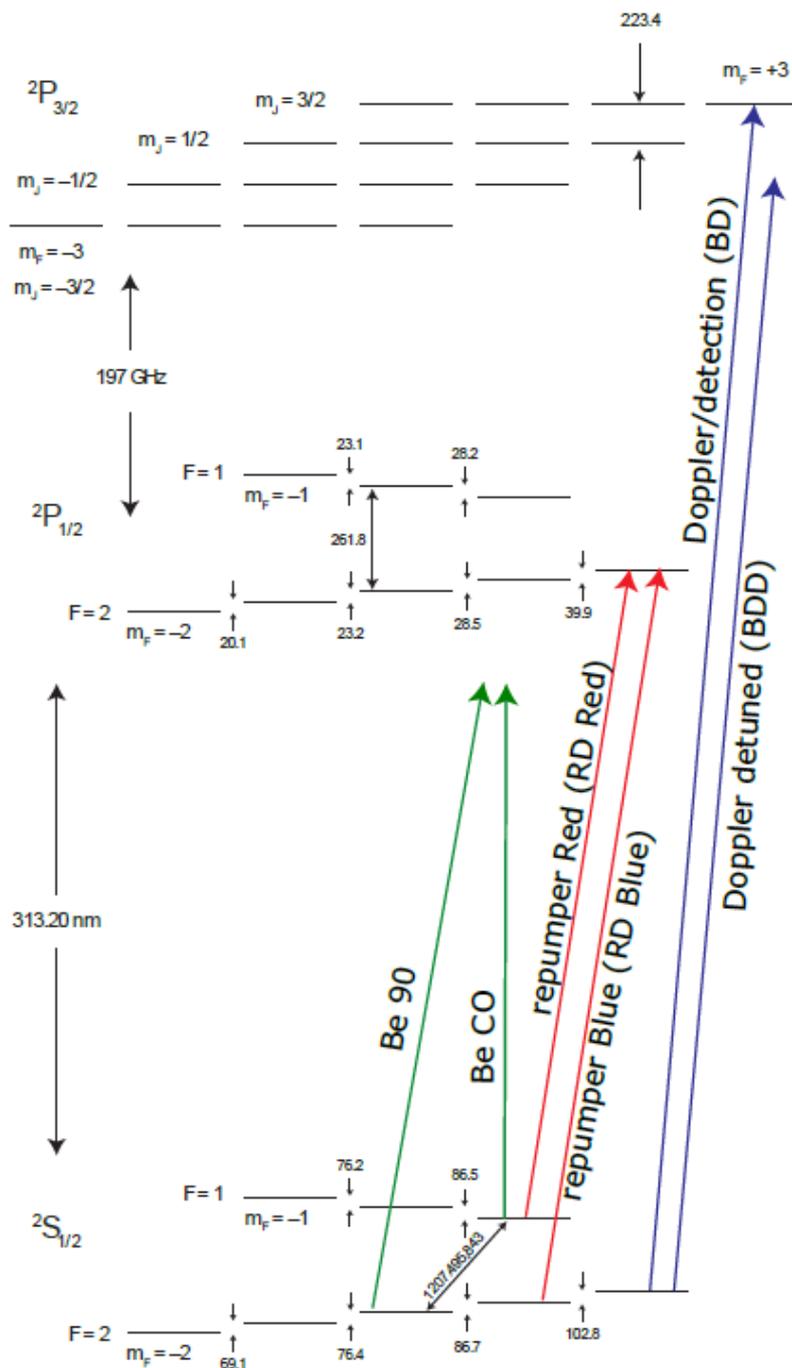
阱里面的离子，  
单束激光即可多  
普勒冷却

# Be<sup>+</sup> 离子能级

$$2S+1 L_J$$

- 一个外层电子,  $S=1/2$
- 基态  $L=0, J=1/2$
- 核自旋  $I=3/2$
- 超精细耦合  $F=J+I=1, 2$
- 外加  $0.01\text{T}$  磁场塞曼分裂  $\sim 10\text{'s MHz}$

- $2S_{1/2}$
- $2P_{1/2}$      $2P_{3/2}$



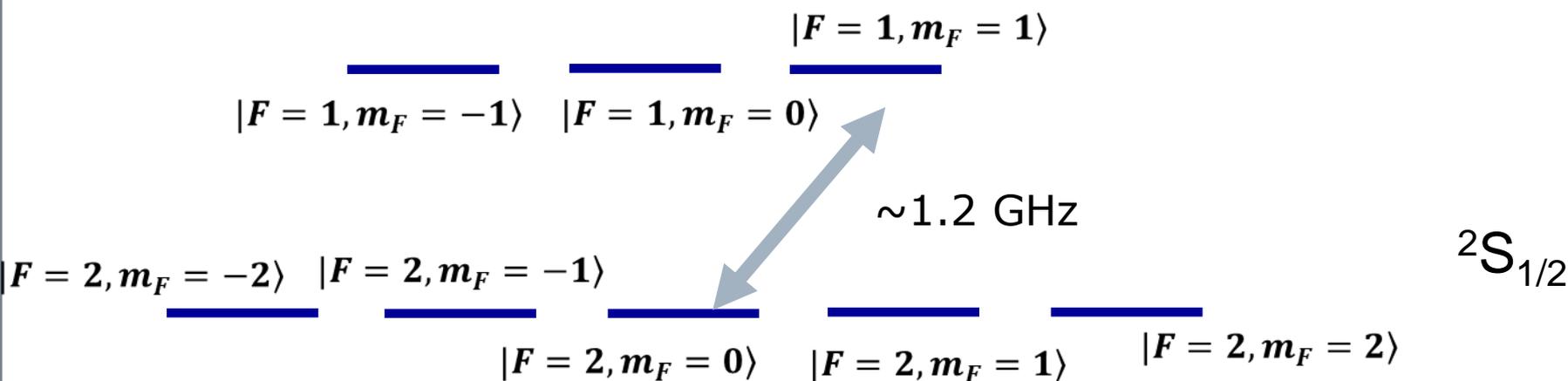
# ${}^9\text{Be}^+$ 离子

Qubit: Beryllium ion  ${}^9\text{Be}^+$  ( $I = 3/2$ )  
类氢离子

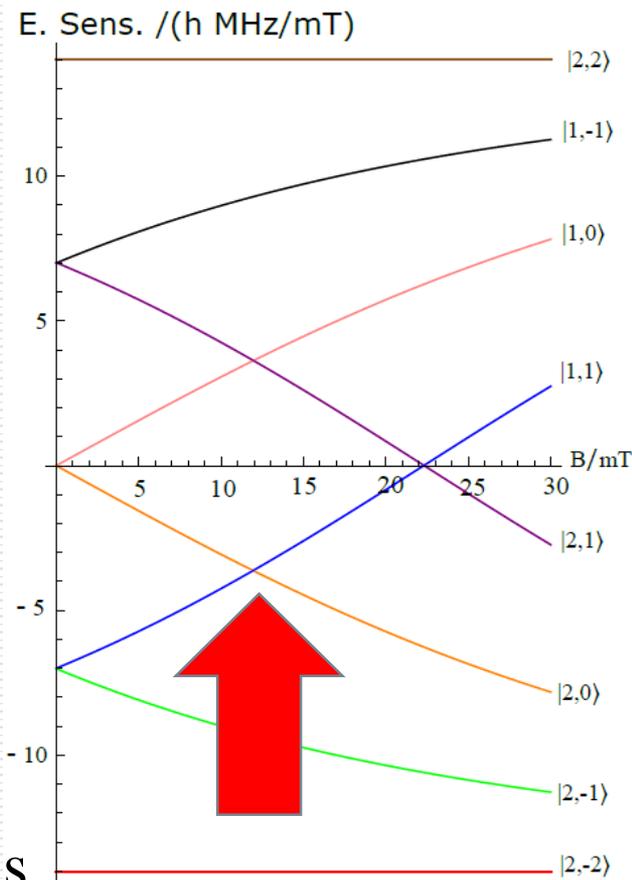
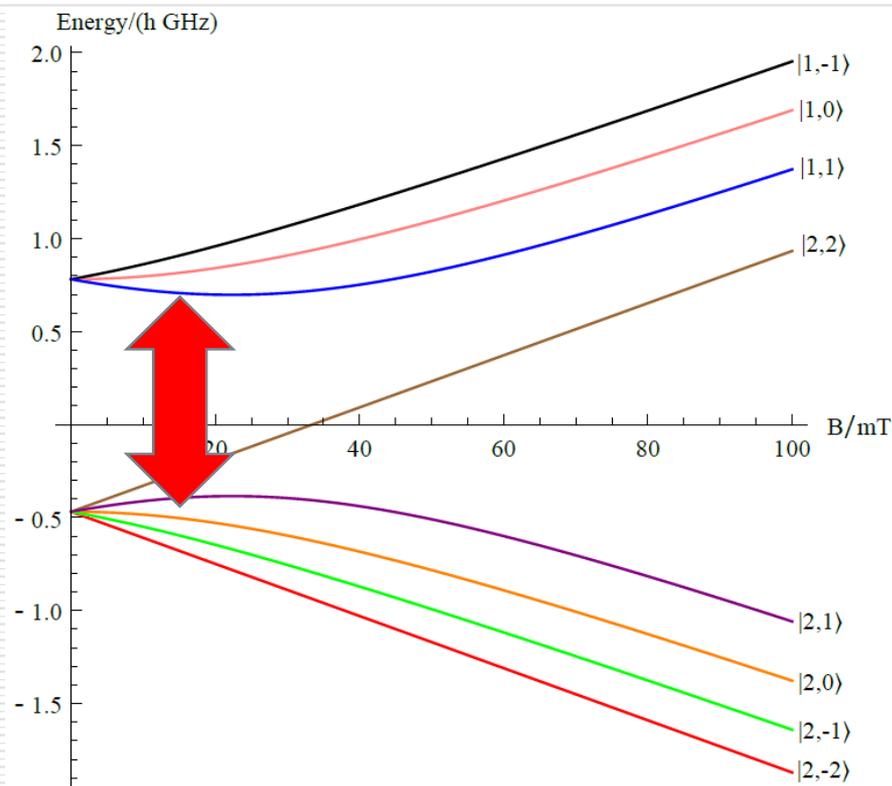
一阶磁场涨落不敏感  
 $B = 0.0119446$  Tesla  
自旋相干寿命  $\sim s$

hydrogen 1 1.0079	
lithium 3 6.941	beryllium 4 9.0122
sodium 11 22.990	magnesium 12 24.305
potassium 19 39.098	calcium 20 40.078
rubidium 37 85.468	strontium 38 87.62

scandium 21 44.956
yttrium 39 88.906



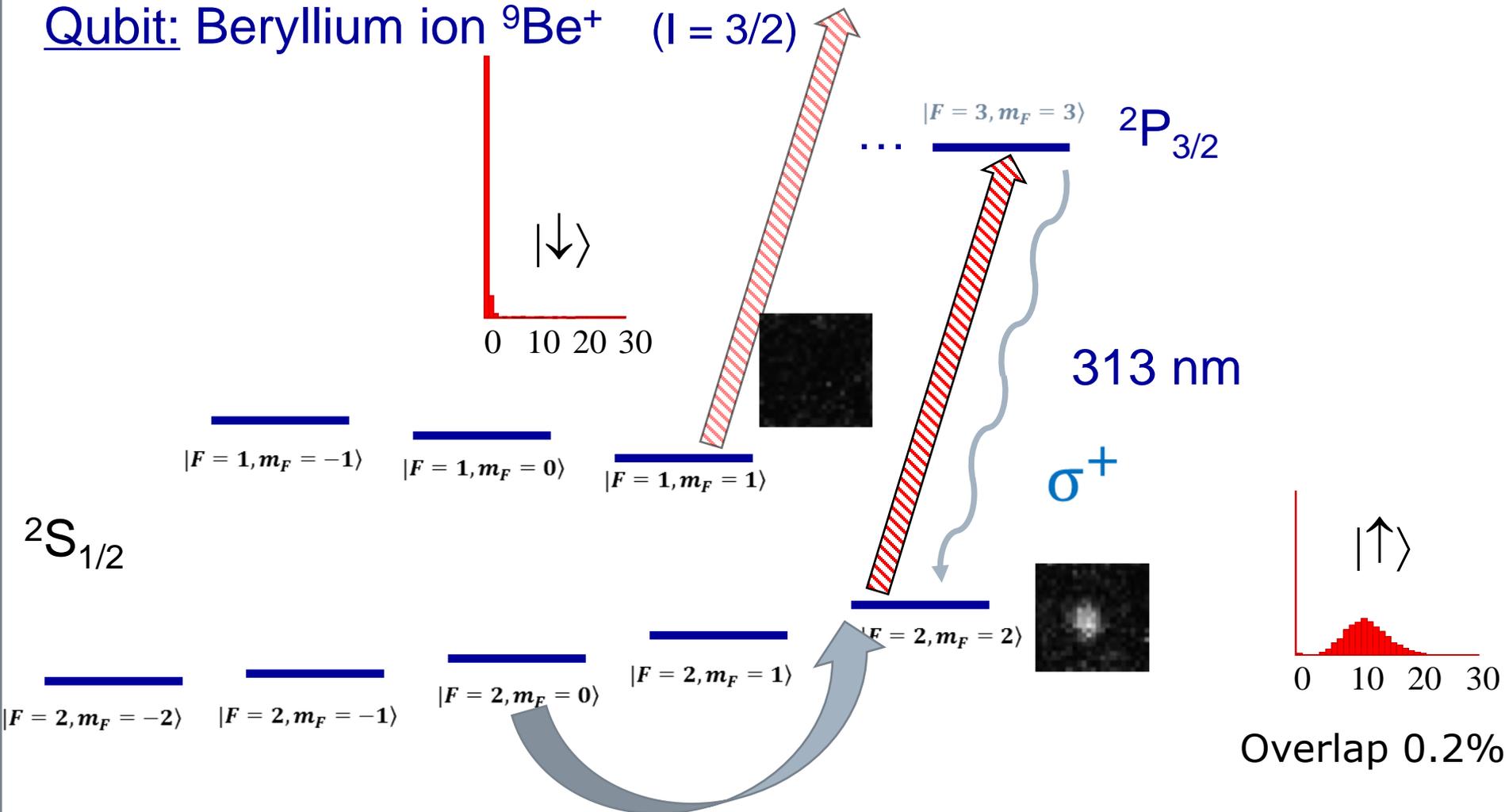
# 磁场涨落不敏感



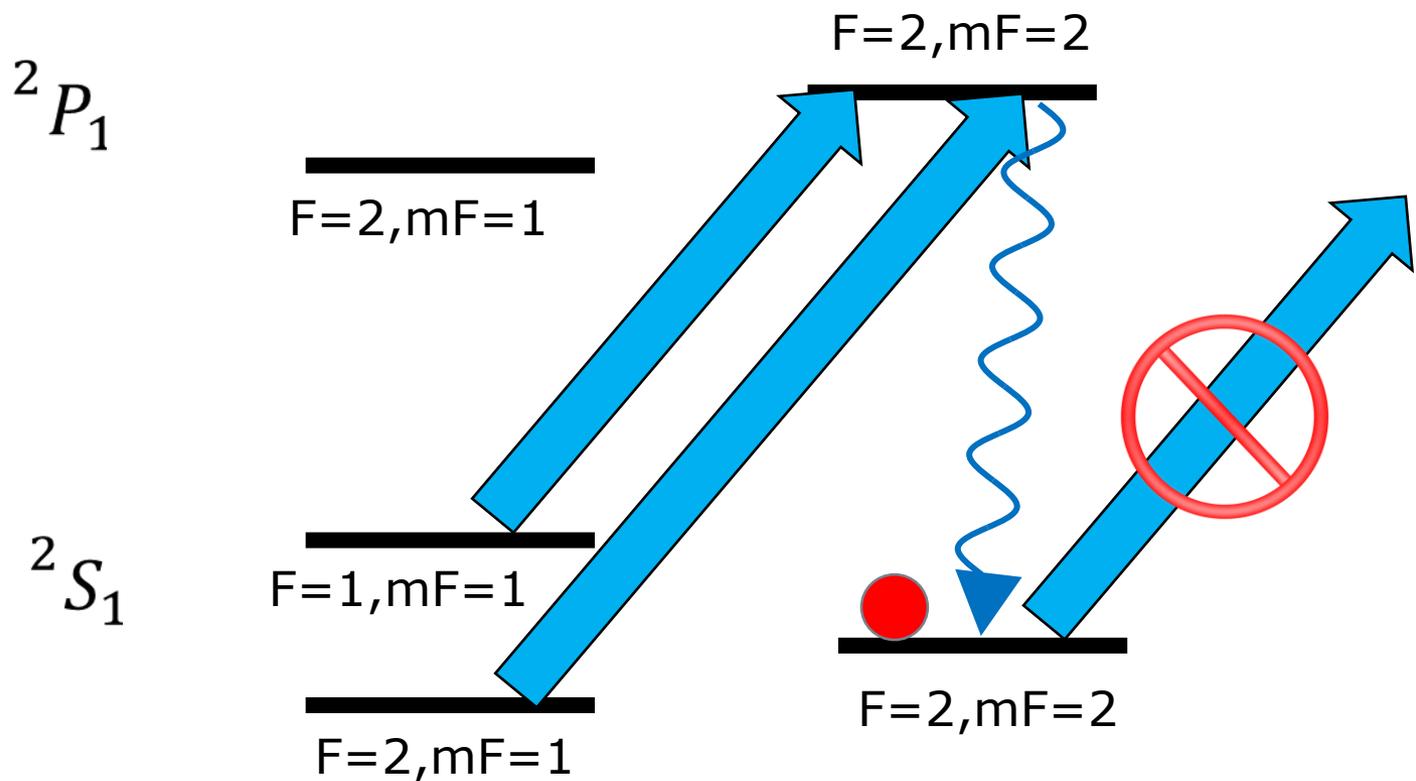
一阶塞曼效应为0，自旋相干 $\sim 1$  s

# 自旋探测 - 循环跃迁

Qubit: Beryllium ion  ${}^9\text{Be}^+$  ( $I = 3/2$ )



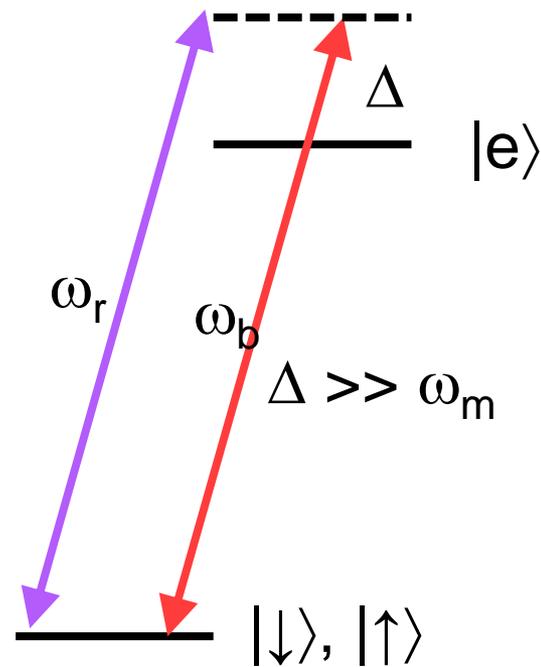
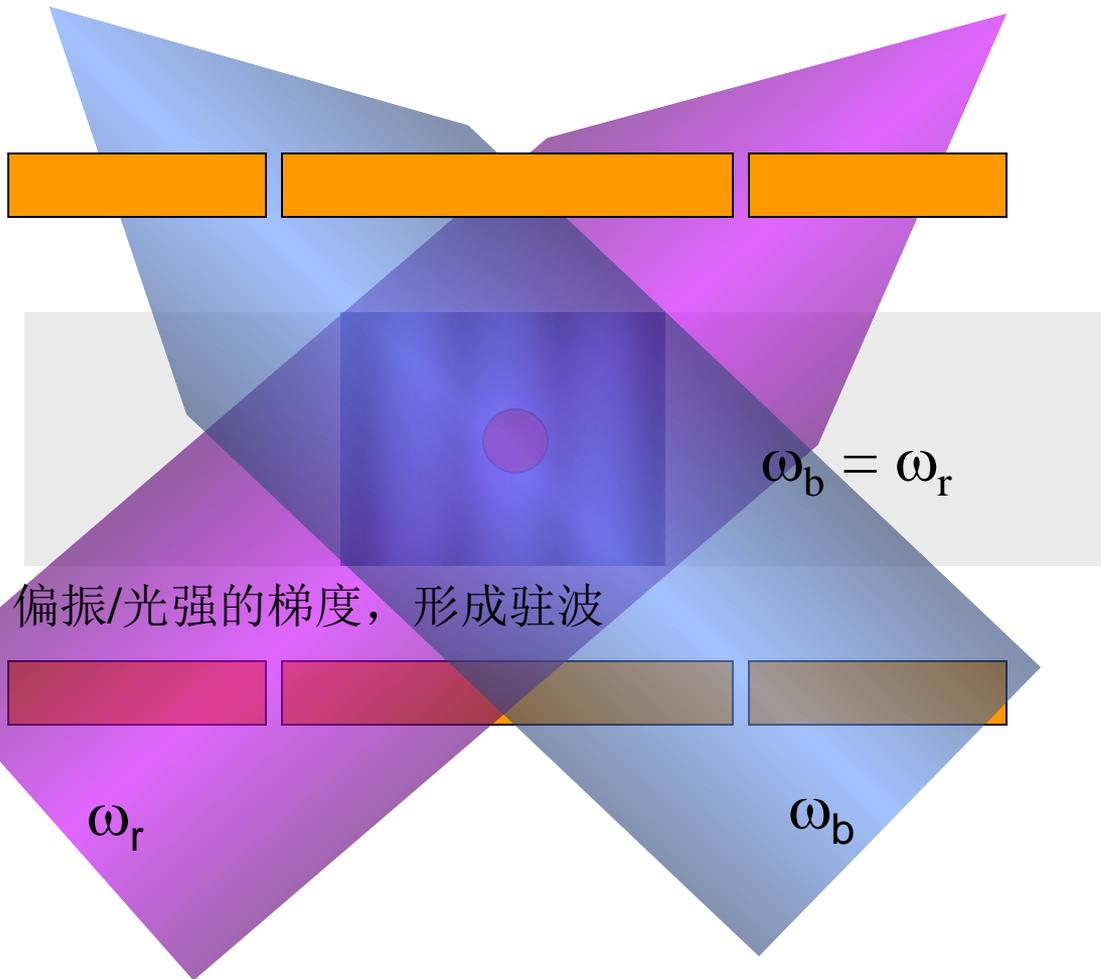
# 自旋制备-光学泵浦



利用激光的偏振 $\sigma^+$ ，激发  
选择定则 $mF \rightarrow mF+1$

# 两比特相位门：光学耦极力

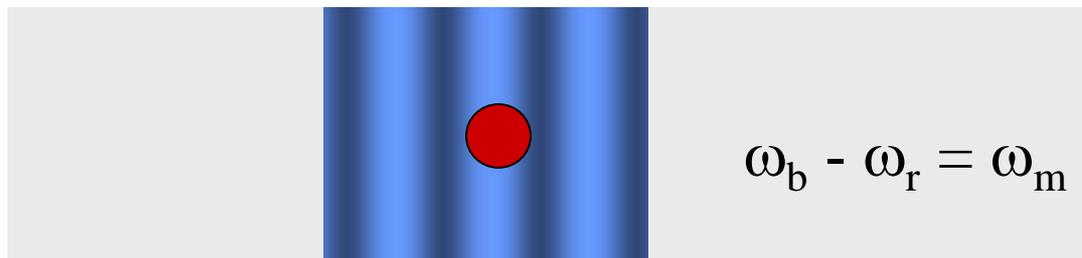
● 离子振动频率  $\omega_m$   
↔



基本想法：使用  
**Stark**效应的梯度  
对  $|\downarrow\rangle$  和  $|\uparrow\rangle$  态施加  
不同的作用力

● 离子振动频率  $\omega_m$

↔

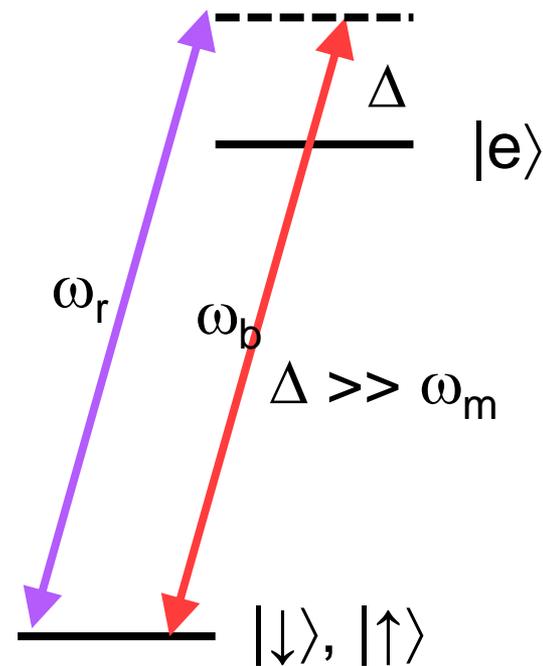


$$\omega_b - \omega_r = \omega_m + \delta$$

“运动”驻波



example: make  $F_{\uparrow} = -F_{\downarrow}$

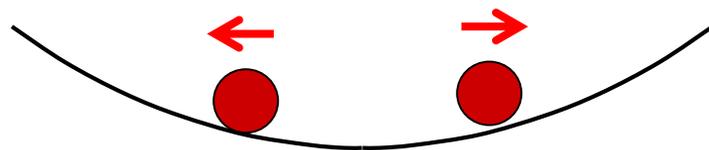


基本想法: 使用  
**Stark**效应的梯度  
对 $|\downarrow\rangle$  和  $|\uparrow\rangle$  态施加  
不同的作用力

# 两离子(例如stretch mode):

$$\omega_b - \omega_a = \omega_{\text{stretch}} + \delta$$

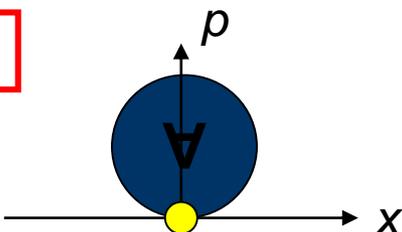
$$\text{作用力 } t = 2\pi/\delta$$



“stretch” mode

假设  $F_{\uparrow} = -F_{\downarrow}$

$|\downarrow\rangle|\uparrow\rangle$ :

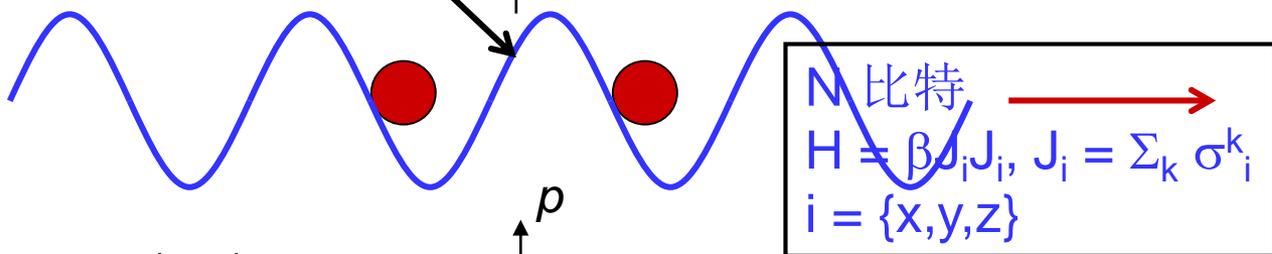


$|\downarrow\rangle|\uparrow\rangle \rightarrow i |\downarrow\rangle|\uparrow\rangle$   
 $|\uparrow\rangle|\downarrow\rangle \rightarrow i |\uparrow\rangle|\downarrow\rangle$

一般情况:

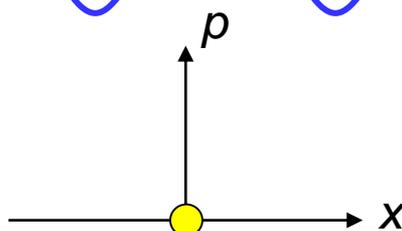
$$i \rightarrow e^{i\phi}$$

移动的耦极作用力梯度



$$\omega_b - \omega_r = \omega_m + \delta$$

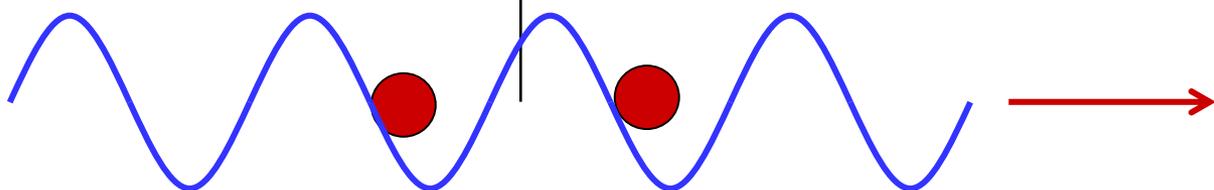
$|\downarrow\rangle|\downarrow\rangle$ :



$|\downarrow\rangle|\downarrow\rangle \rightarrow |\downarrow\rangle|\downarrow\rangle$   
 $|\uparrow\rangle|\uparrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$

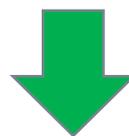
两比特量子门误差

$$8 \times 10^{-4}$$



# 纠缠态

$$|\uparrow\rangle|\uparrow\rangle$$



单比特翻转

$$|\uparrow\rangle|\uparrow\rangle + |\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle + |\downarrow\rangle|\downarrow\rangle$$



两比特相位门

$$|\uparrow\rangle|\uparrow\rangle + i|\uparrow\rangle|\downarrow\rangle + i|\downarrow\rangle|\uparrow\rangle + |\downarrow\rangle|\downarrow\rangle$$



单比特翻转

$$|\uparrow\rangle|\uparrow\rangle + |\downarrow\rangle|\downarrow\rangle$$

# 扩展到多个离子

形成有效的哈密顿量

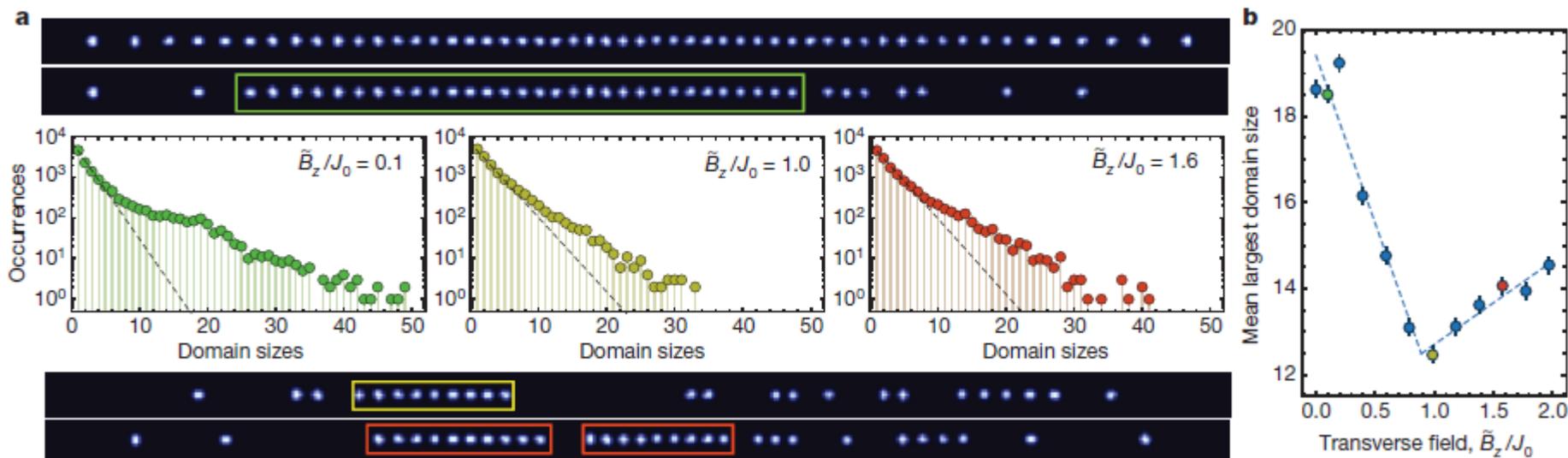
$$H = \sum_{ij} J_{ij} \sigma_{\phi,i} \sigma_{\phi,j}$$

模拟Ising模型等，例如53个离子的量子模拟， $J \sim 1$  kHz

相互作用程可调

$$J_{ij} \propto \frac{1}{|i-j|^\alpha},$$

$0.05 < \alpha < 1.4$

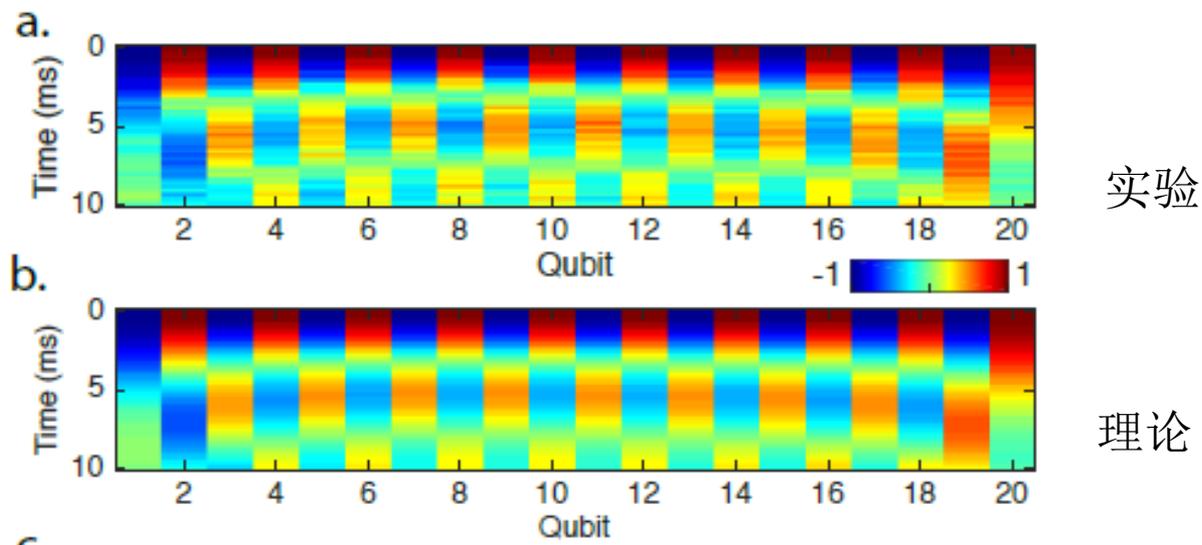


# 扩展到多个离子

## Observation of entangled states of a fully-controlled 20 qubit system

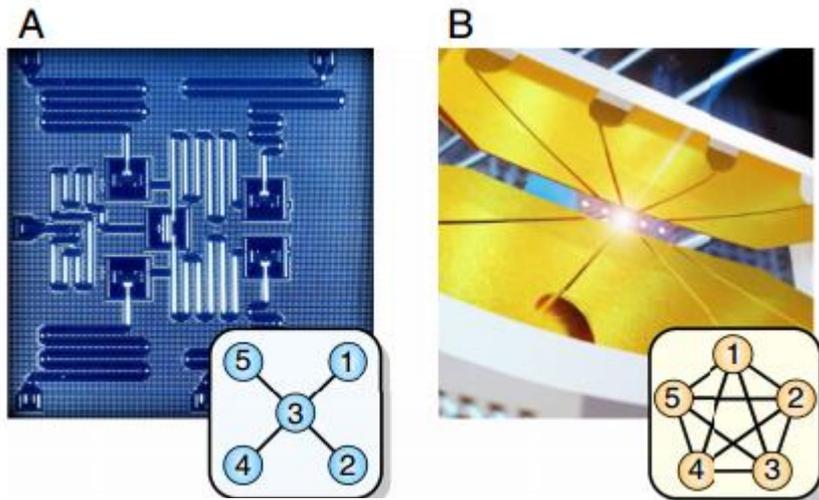
Nicolai Friis,<sup>1,\*</sup> Oliver Marty,<sup>2,\*</sup> Christine Maier,<sup>3,4</sup> Cornelius Hempel,<sup>3,4,†</sup> Milan Holzäpfel,<sup>2</sup> Petar Jurcevic,<sup>3,4</sup> Martin Plenio,<sup>2</sup> Marcus Huber,<sup>1</sup> Christian Roos,<sup>3</sup> Rainer Blatt,<sup>3,4</sup> and Ben Lanyon<sup>3,‡</sup>

- 激光聚焦到离子链的任意位置
- 全局的离子耦合离子自旋



# Notable recent ion experiments

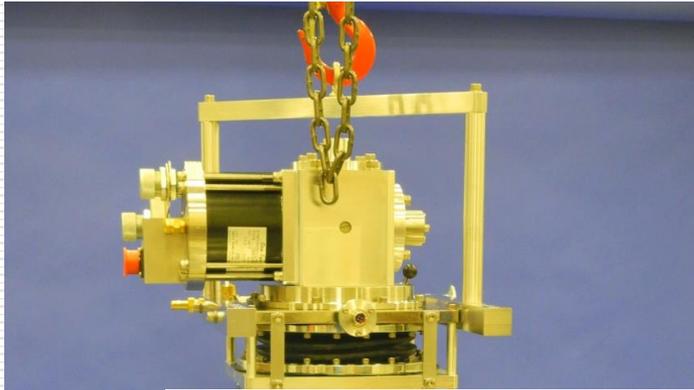
Five ions compared with IBM quantum experience - five superconducting qubits



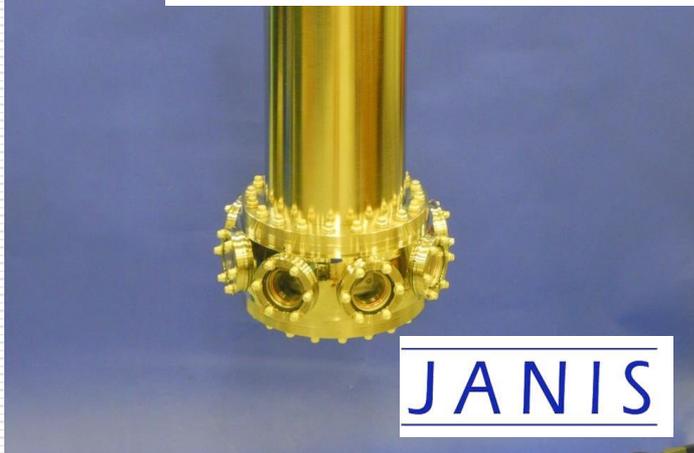
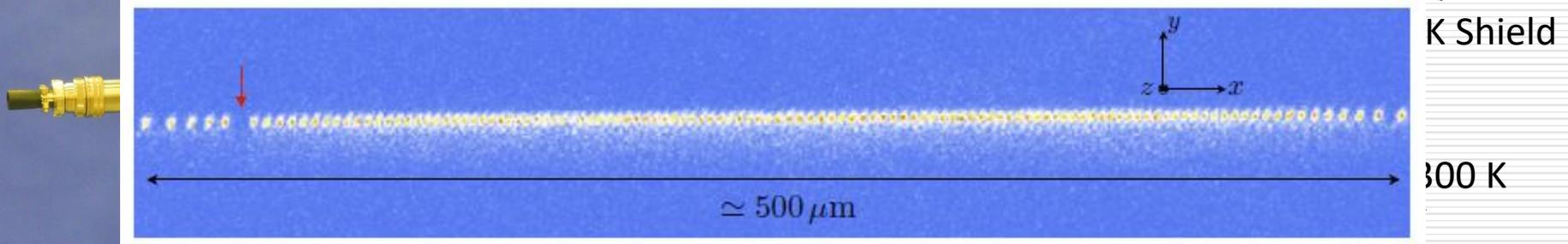
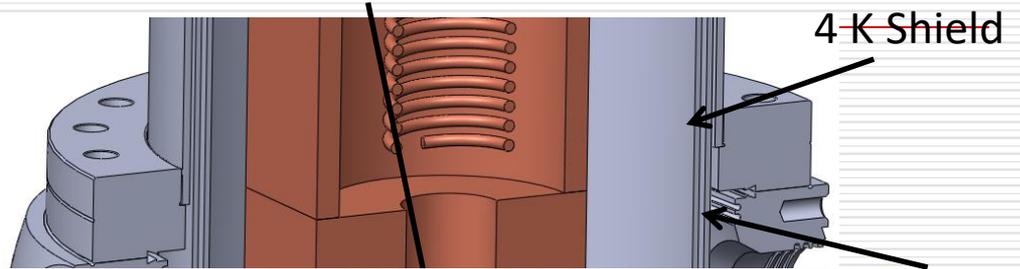
**Table 2. Summary of the achieved success probabilities for the implemented circuits, in percentages**

Connectivity	Star shaped			Fully connected		
	Superconducting			Ion trap		
Hardware	Obs	Rand	Sys	Obs	Rand	Sys
Success probability/%						
Margolus	74.1(7)	82	75	90.1(2)	91	81
Toffoli	52.6(8)	78	59	85.0(2)	89	78
Bernstein–Vazirani	72.8(5)	80	74	85.1(1)	90	77
Hidden shift	35.1(6)	75	52	77.1(2)	86	57

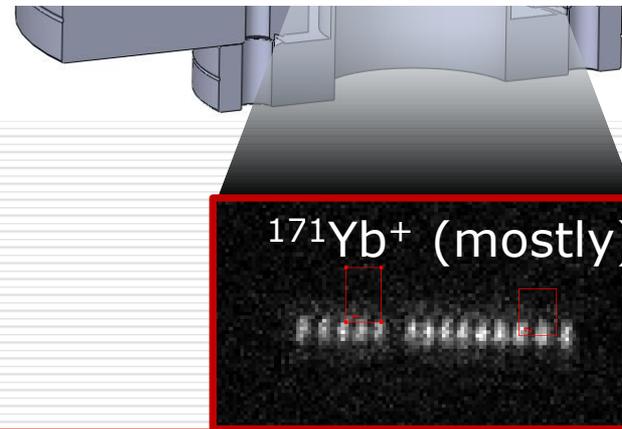
# Scaling Up: 4K to get lower pressure



5-segment linear rf ion trap  
(Au on  $\text{Al}_2\text{O}_3$  blades,  $200\mu\text{m}$ )



JANIS



Credit: Monroe group

# Take home message

- 什么是离子阱

真空中使用电场磁场囚禁带电粒子，特别是原子，分子，颗粒等。可以用作量子信息，原子钟，物理常数的精密测量等研究

- 什么是量子模拟

使用一个容易操控测量的量子体系去模拟较难的物理体系，实验测量得出有用信息

- 什么是量子计算

使用多个可以精密操控的量子比特实现量子算法，某些问题上可能比经典算法优越

Questions?