离子阱物理简介 II

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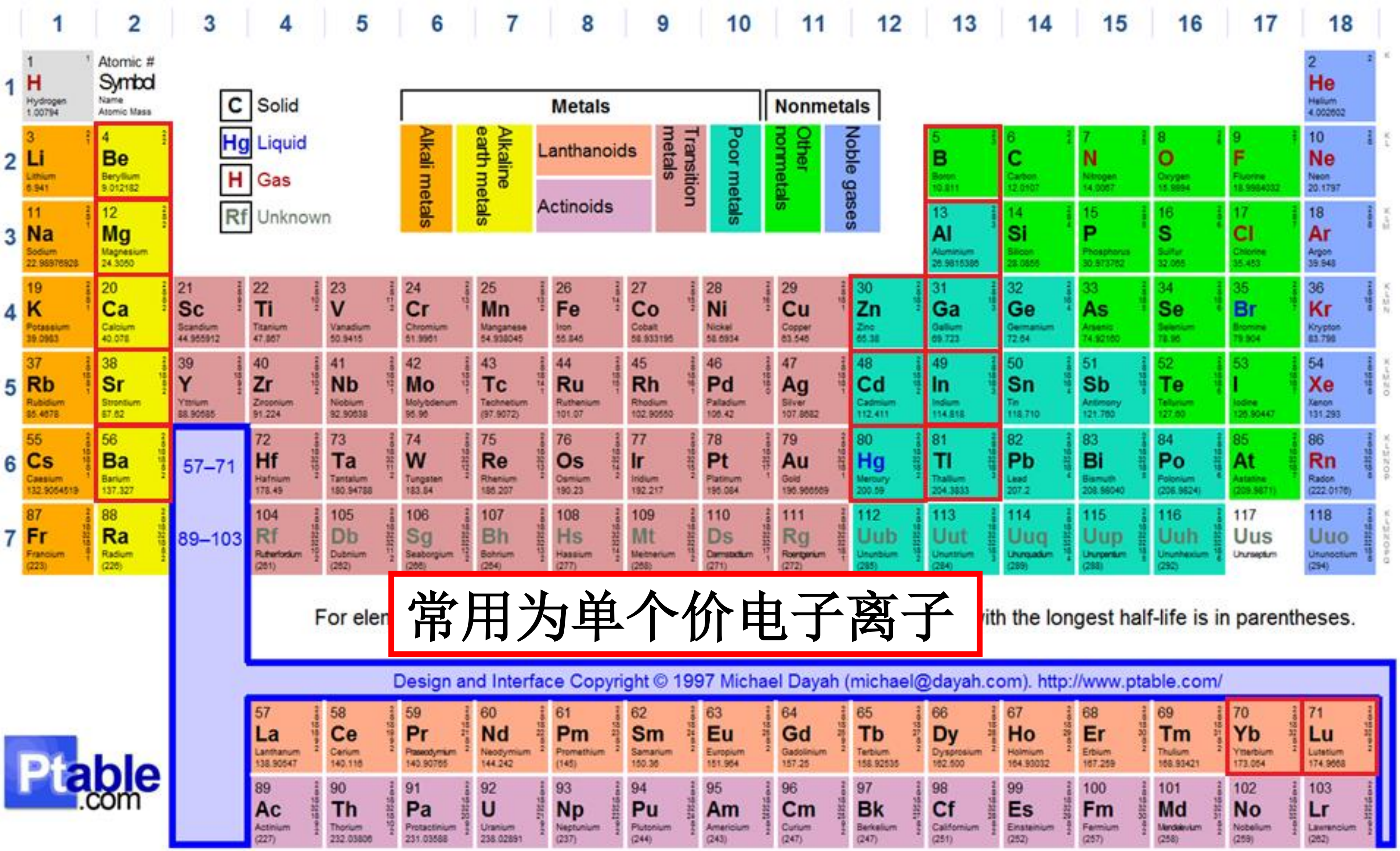
内容

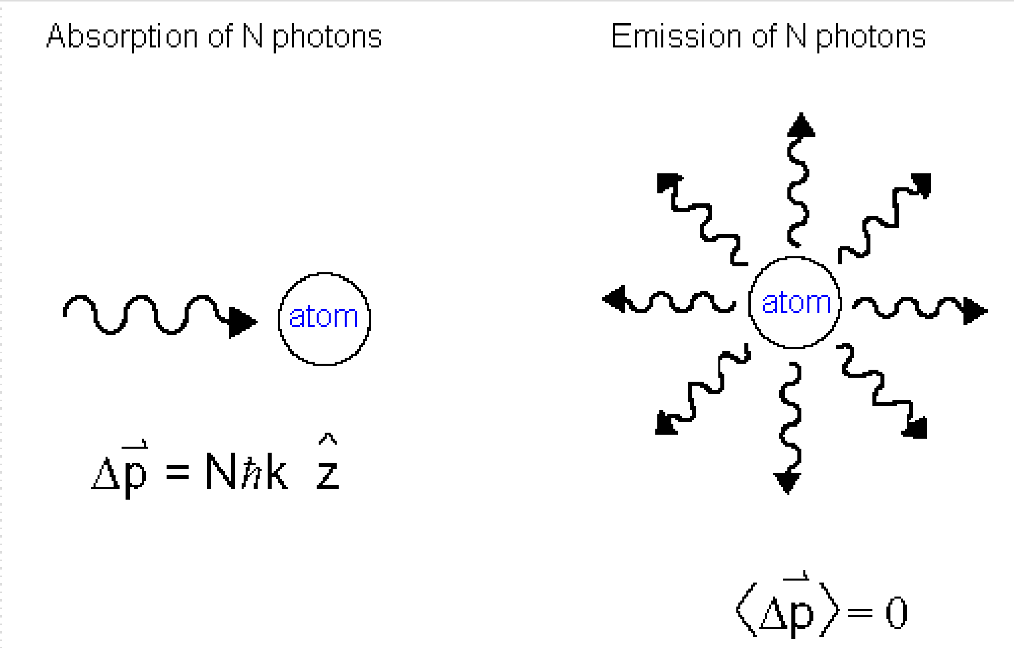
- 背景介绍
- 自组织的离子链
- 光与离子的相互作用
- 量子计算和量子模拟

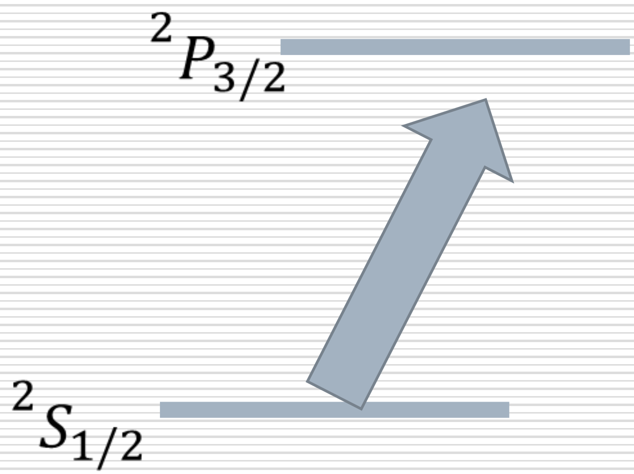
Periodic Table of Elements

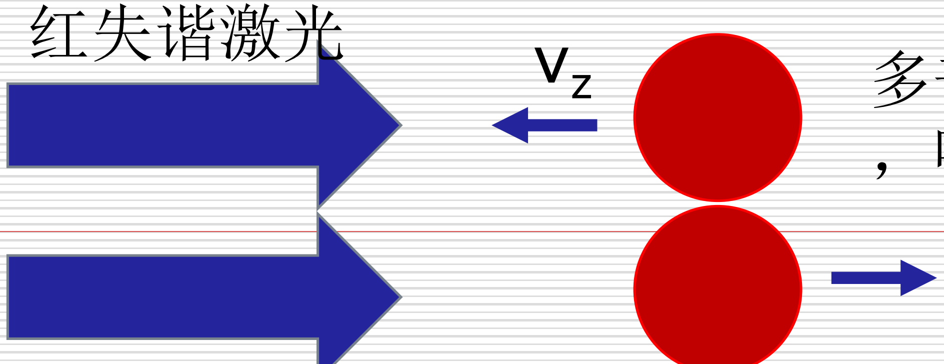


常用为单个价电子离子

激光冷却-多普勒-失谱



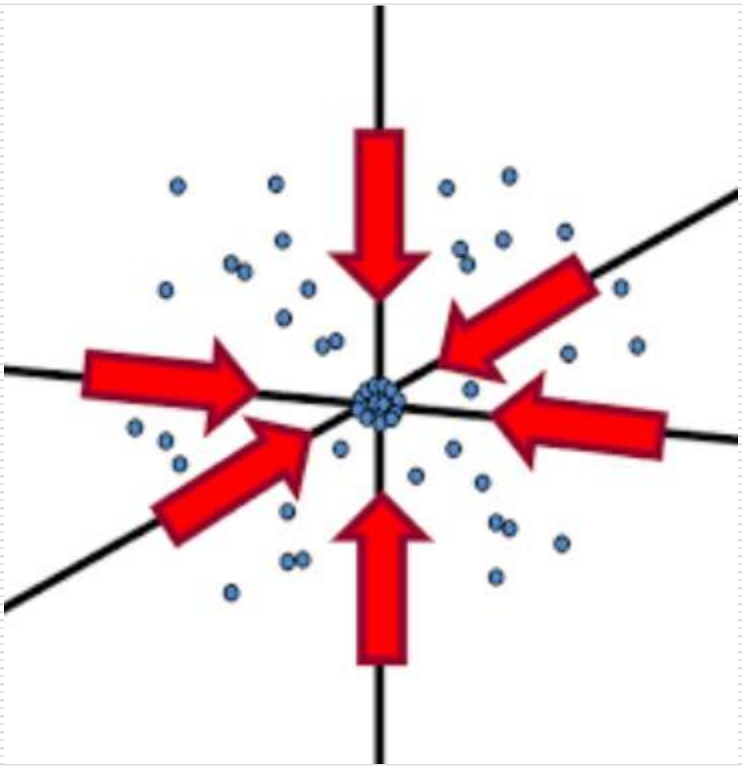




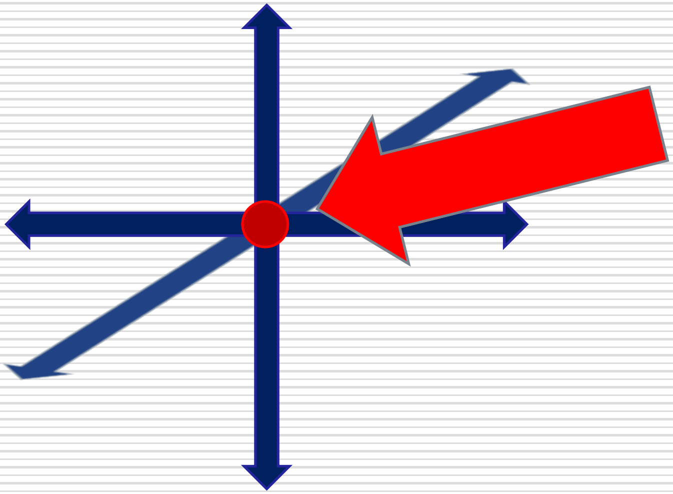
多普勒移动，更接近共振，吸收动量

更远离共振，散射较弱

激光冷却-多普勒



非约束原子，三维冷却，六束激光



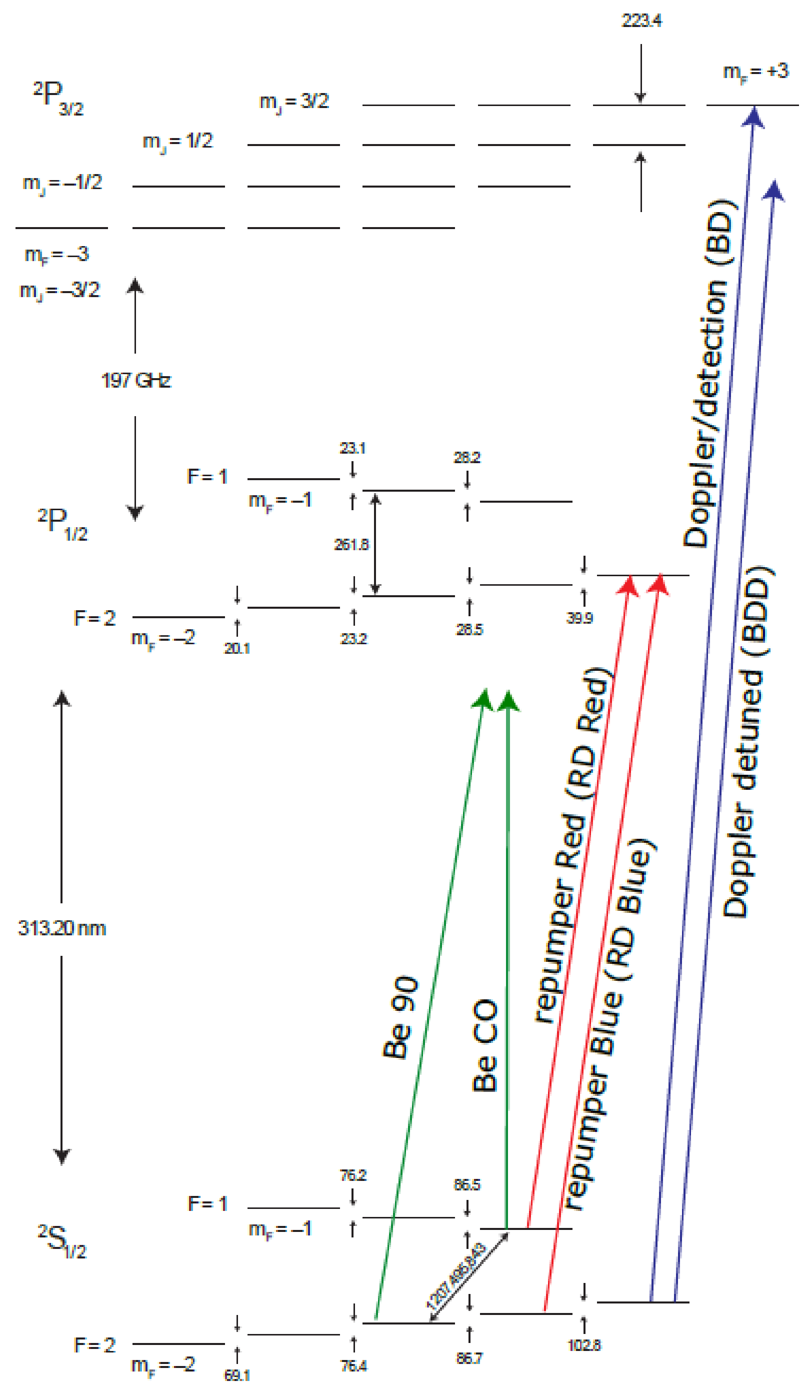
阱里面的离子，单束激光即可多普勒冷却

Be+离子能级

$$^{2S+1}L_J$$

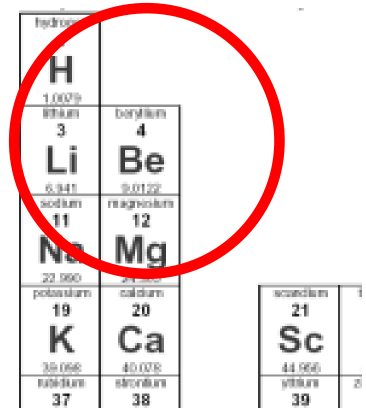
- 一个外层电子，S=1/2
- 基态L=0, J=1/2
- 核自旋I=3/2
- 超精细耦合F=J+I=1,2
- 外加0.01T磁场塞曼分裂 ~10's MHz

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

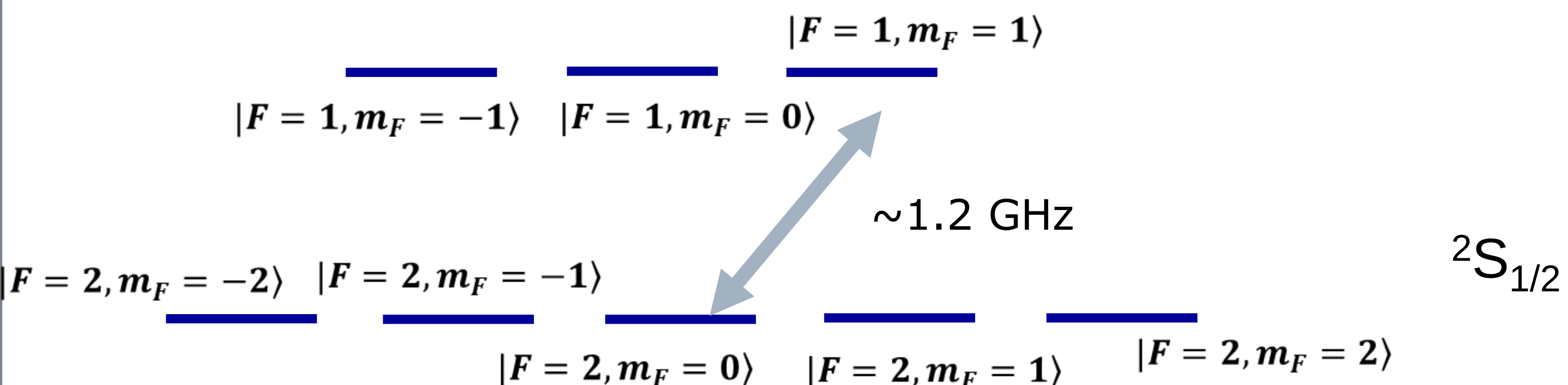


$^{9}Be^{+}$ 离子

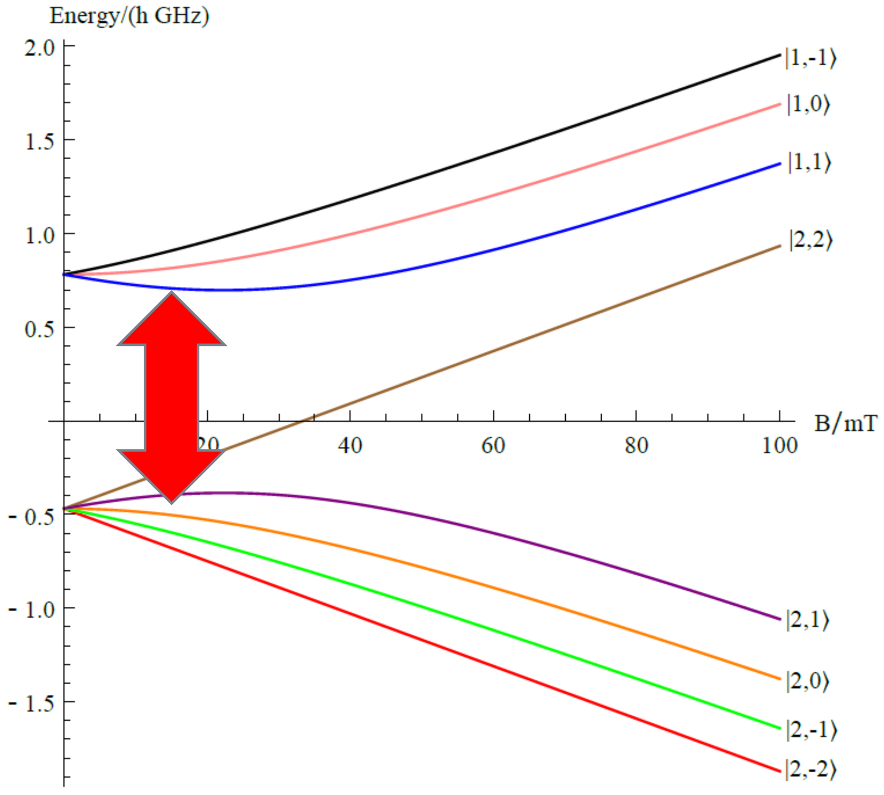
Qubit: Beryllium ion $^{9}Be^{+}$ (I = 3/2)
类氢离子

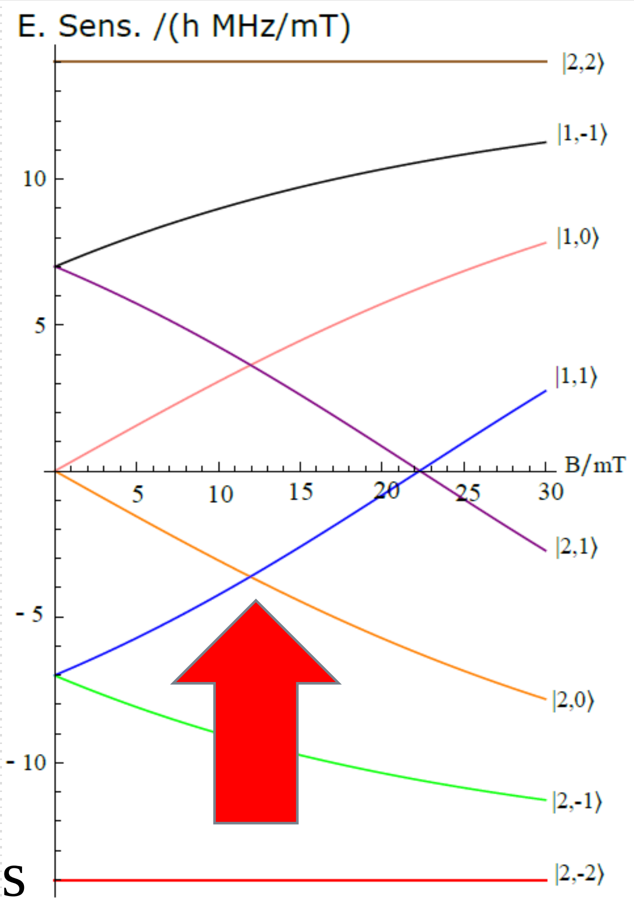


一阶磁场涨落不敏感
B = 0.0119446 Tesla
自旋相干寿命~s



磁场涨落不敏感

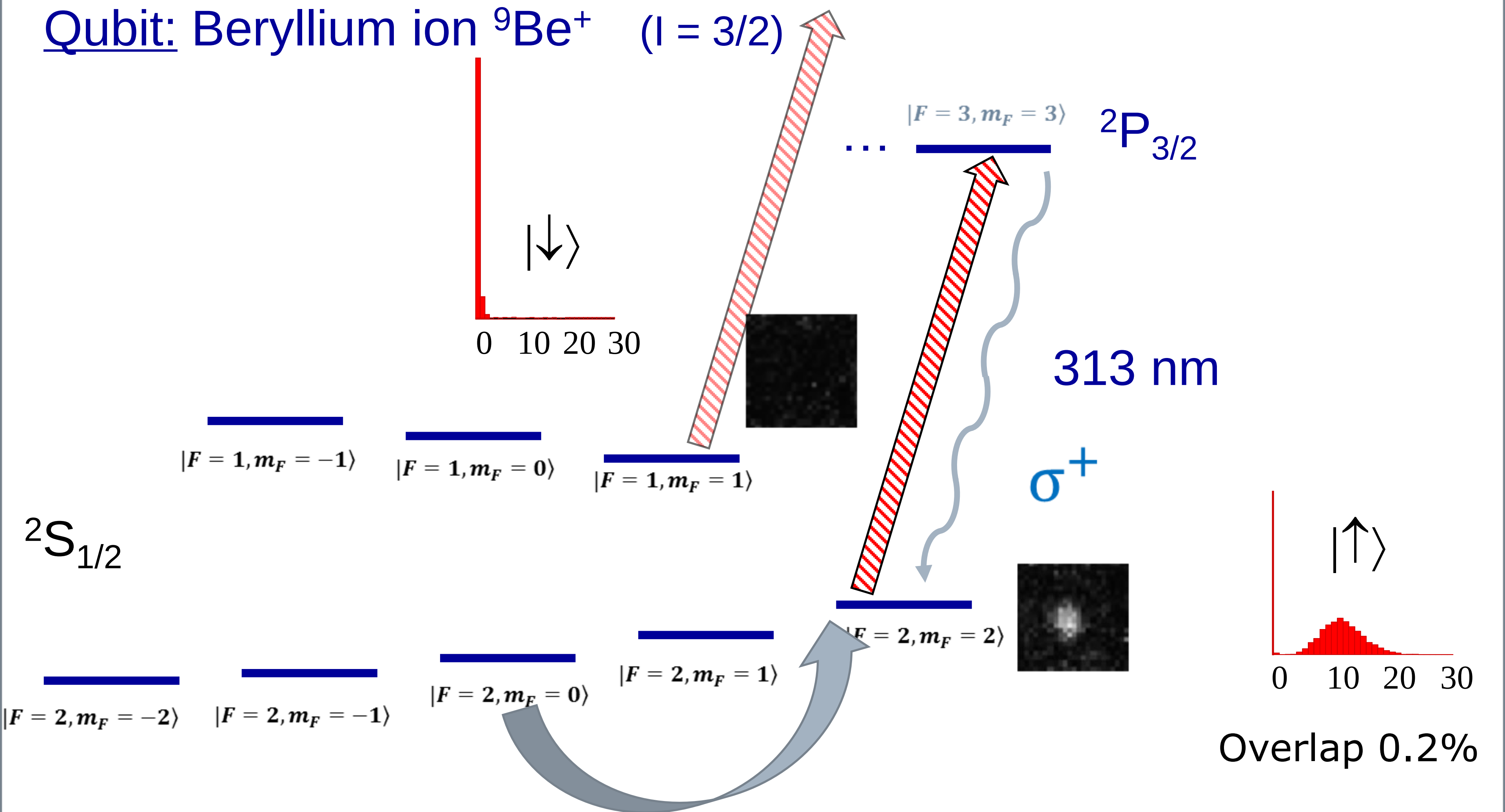




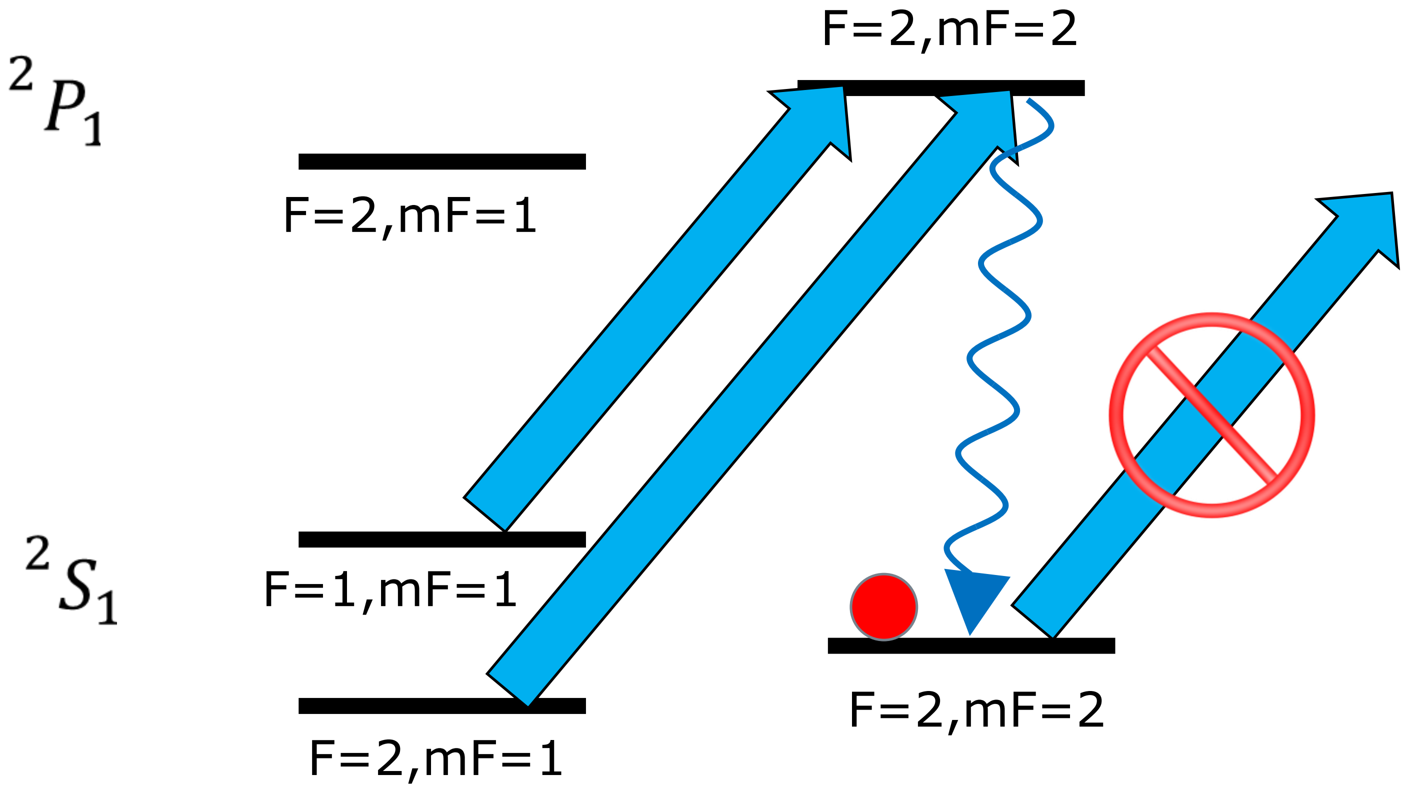
一阶塞曼效应为0，自旋相干~1 s

自旋探测 – 循环跃迁

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

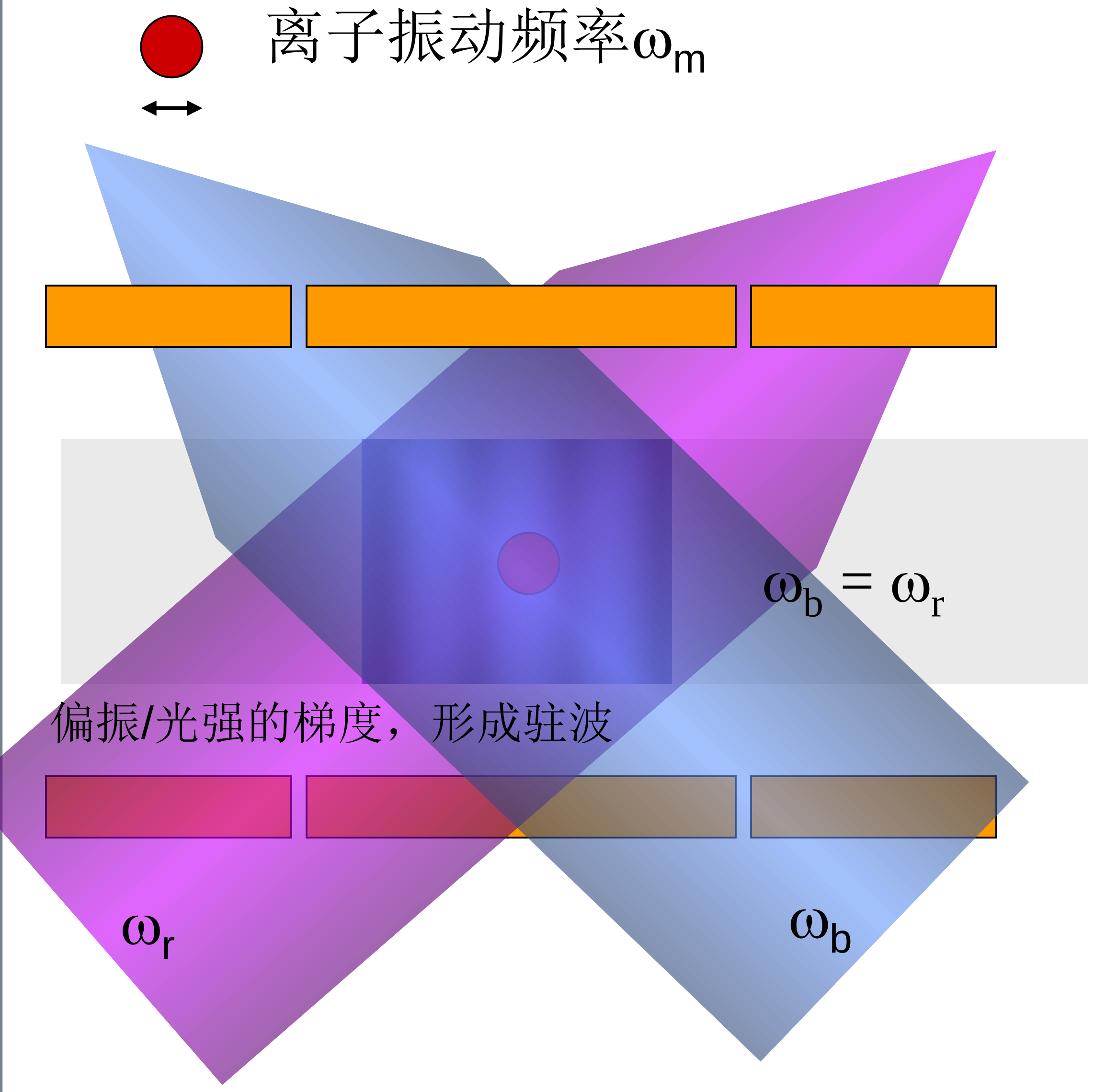


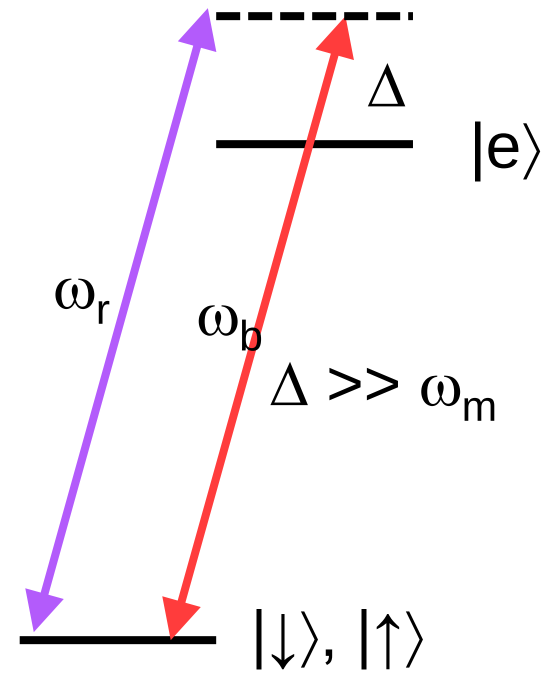
自旋制备-光学泵浦



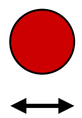
利用激光的偏振σ^+，激发选择定则mF->mF+1

两比特相位门：光学耦极力

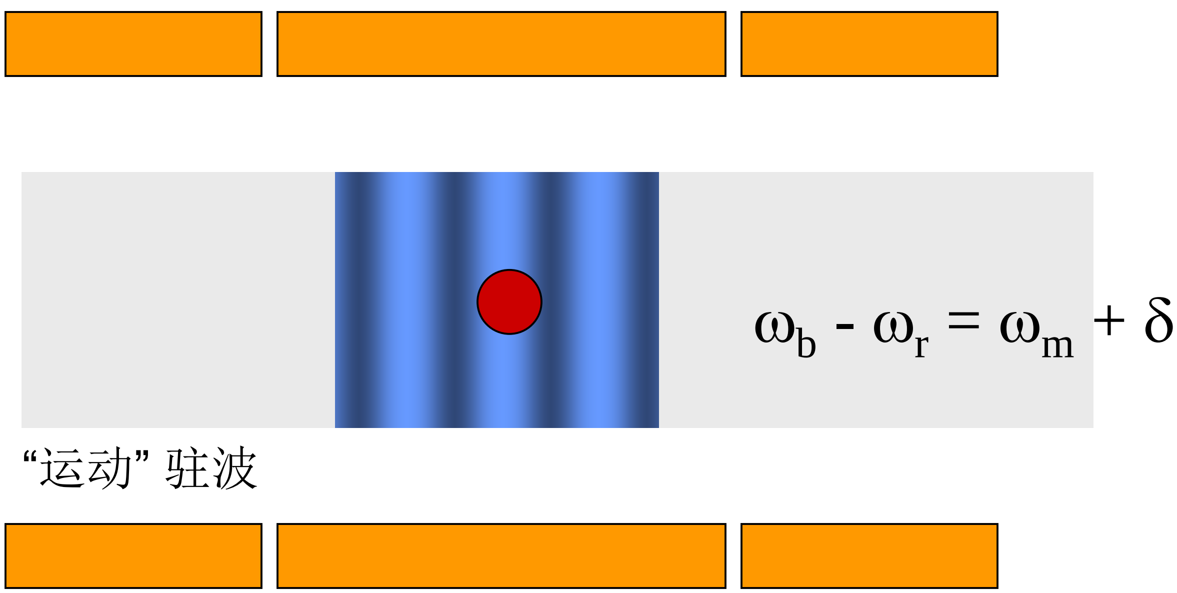


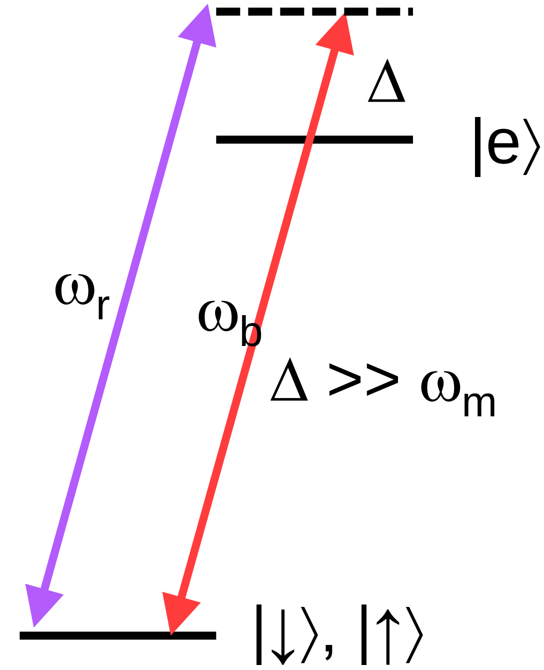


基本想法: 使用
Stark效应的梯度
对$|\downarrow\rangle$ 和 $|\uparrow\rangle$ 态施加
不同的作用力



离子振动频率ω_m





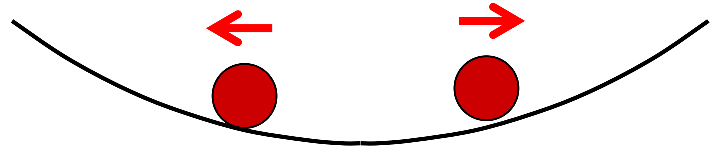
基本想法: 使用
Stark效应的梯度
对$|\downarrow\rangle$ 和 $|\uparrow\rangle$ 态施加
不同的作用力

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

两离子(例如stretch mode):

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

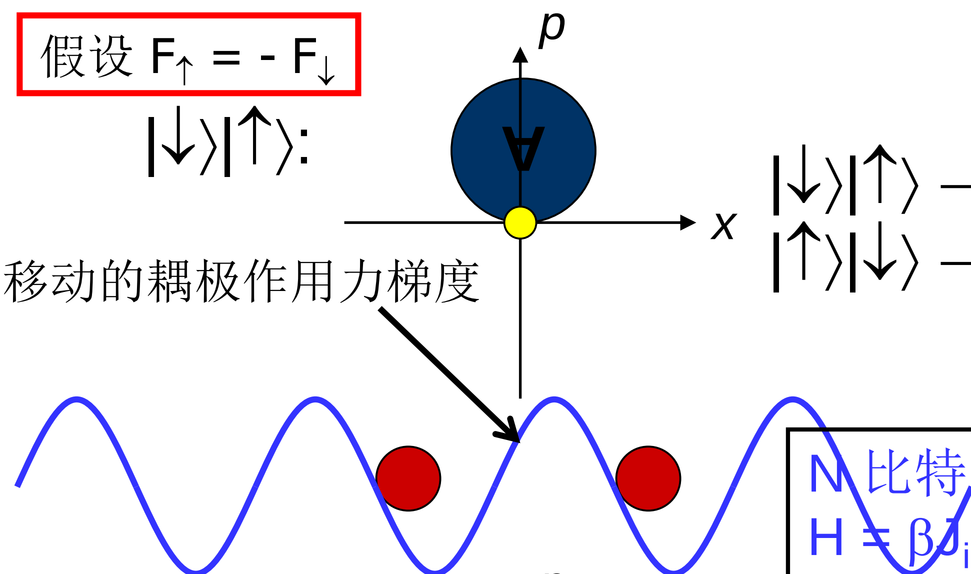
作用力 $t = 2\pi/\delta$



“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:

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

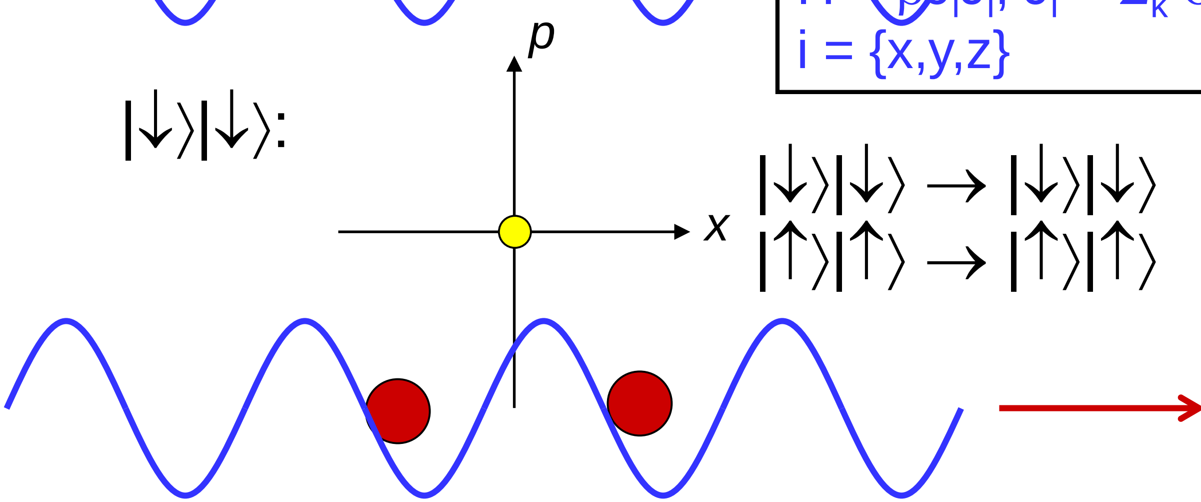
N 比特

$H = \beta J_i J_i,\ J_i = \Sigma_k\, \sigma^k{}_i$

$i = \{x,y,z\}$

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

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



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

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

两比特量子门误差

8×10^{-4}

PRL 117, 060505 (2016); PRL 117, 060504 (2016); PRL **82**, 1971-1974 (1999)

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

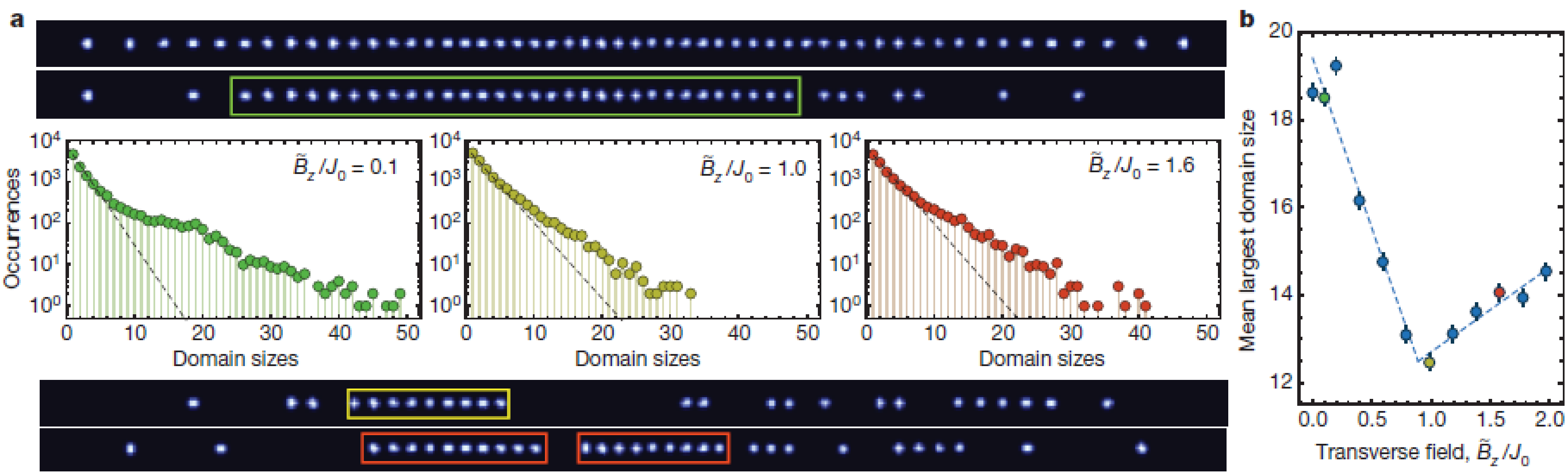
$$H = \sum_{ij} J_{ij}\sigma_{\phi,\mathrm{i}}\sigma_{\phi,\mathrm{j}}$$

相互作用程可调

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

$$0.05 < \alpha < 1.4$$

模拟Ising模型等，例如53个离子的量子模拟，J~1 kHz



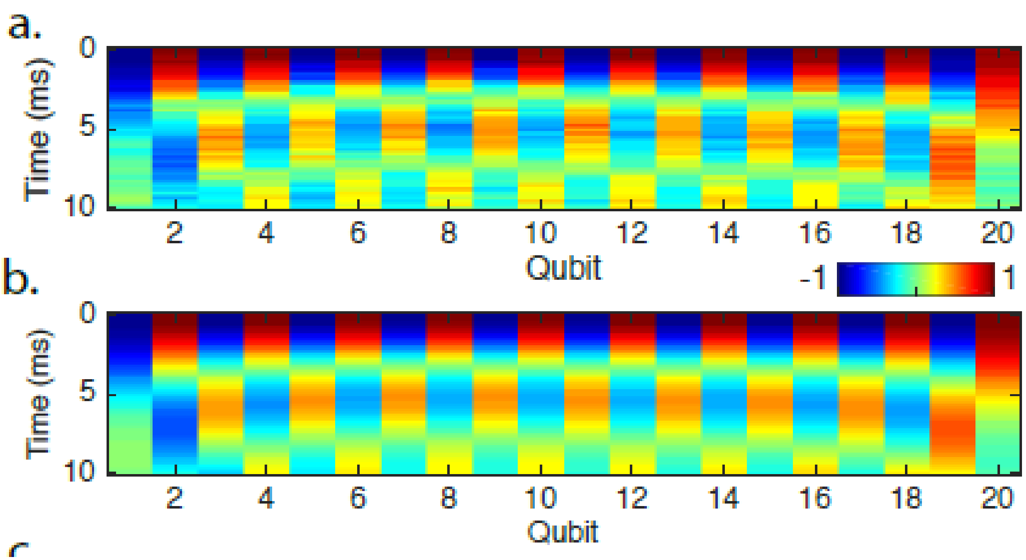
Nature 551, 601, 2017; Nature 484, 489, 2012

扩展到多个离子

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

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

- 激光聚焦到离子链的任意位置
- 全局的离子耦合离子自旋



实验

理论

Friis, N. *et al. Phys. Rev. X* **8**, 021012 (2018).

Notable recent ion experiments

Five ions compared with IBM quantum experience - five superconducting qubits

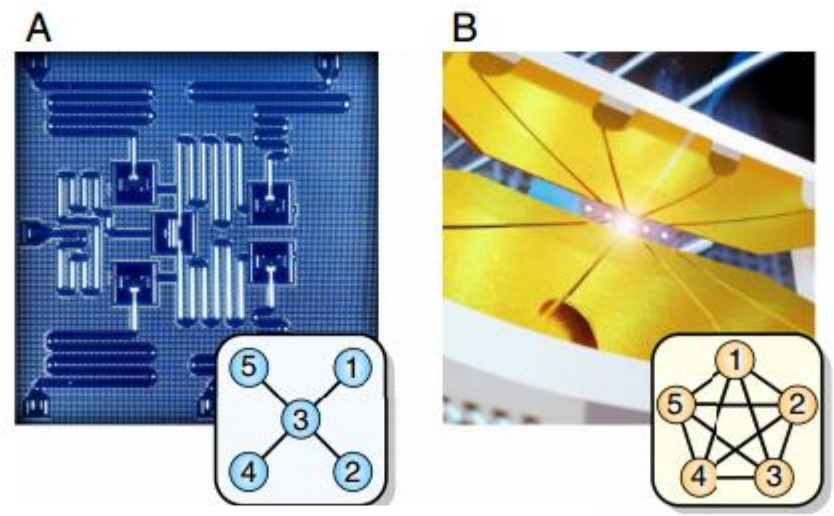
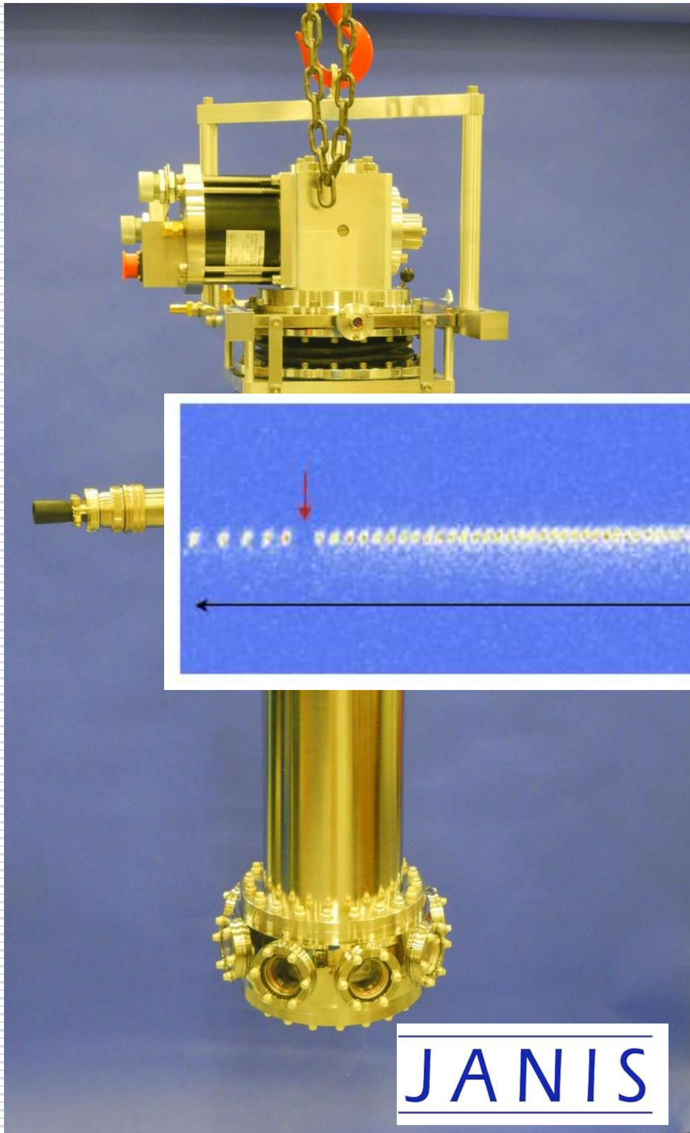


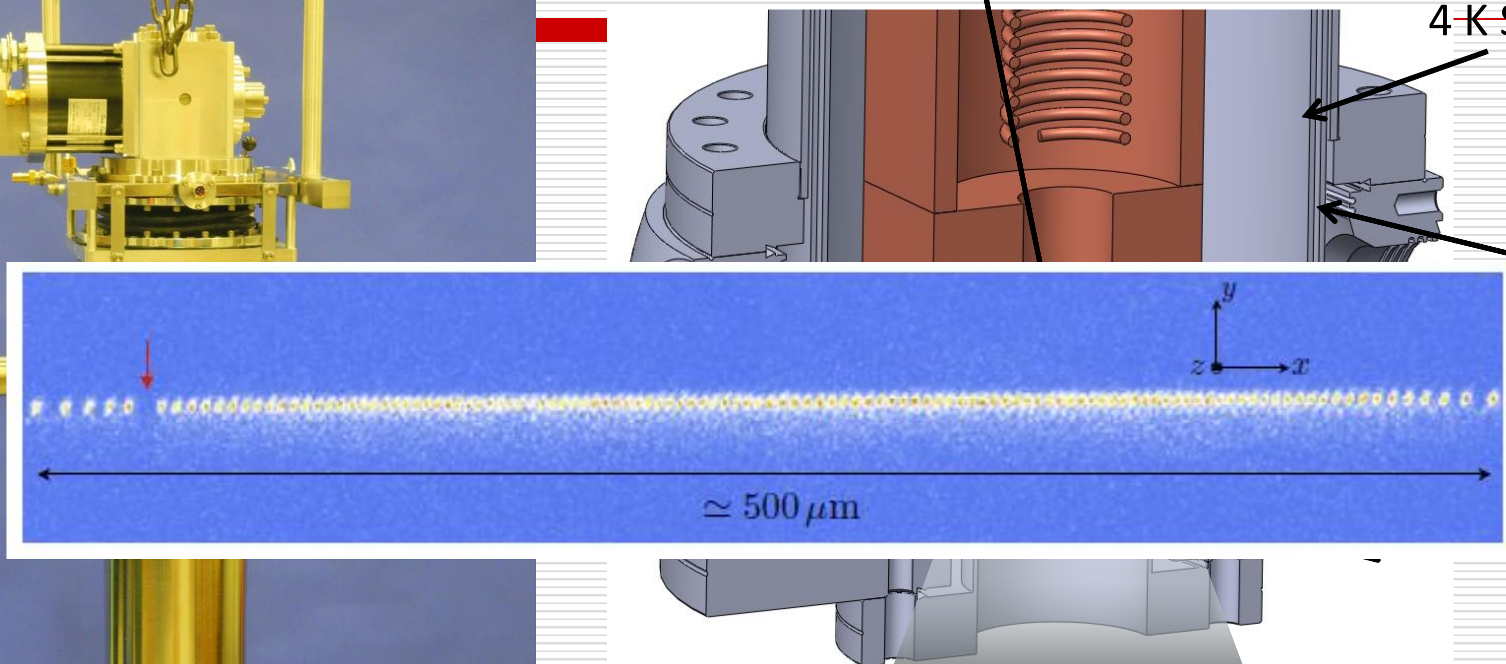
Table 2. Summary of the achieved success probabilities for the implemented circuits, in percentages

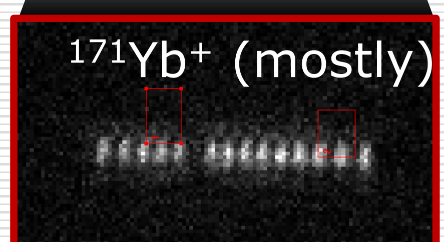
Connectivity	Star shaped			Fully connected		
Hardware	Superconducting			Ion trap		
Success probability/%	Obs	Rand	Sys	Obs	Rand	Sys
Margolus	74.1(7)	82	75	90.1(2)	91	81
Toffoli	52.6(8)	78	59	85.0(2)	89	78
Bernstein–Vazirani	72.8(5)	80	74	85.1(1)	90	77
Hidden shift	35.1(6)	75	52	77.1(2)	86	57

Scaling Up: 4K to get lower pressure



5-segment linear rf ion trap
(Au on Al_2O_3 blades, 200μm)





Credit: Monroe group

Pagano, G. *et al. Quantum Sci. Technol.* (2018) doi:10.1088/2058-9565/aae0fe.

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?