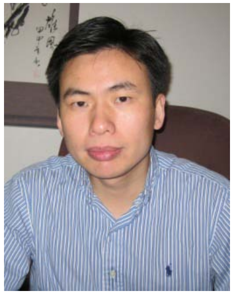
2010 Michigan Quantum Summer School
Quantum Simulation and Metrology
August 2 – 13, 2010





Aaron Leanhardt | Hui Deng | Luming Duan | Chris Monroe | Angela Milliken

University of Michigan

Joint Quantum Institute

U.S. Air Force

Physics University of Michigan

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ICAM-I2CAM Institute for Complex Adaptive Matter

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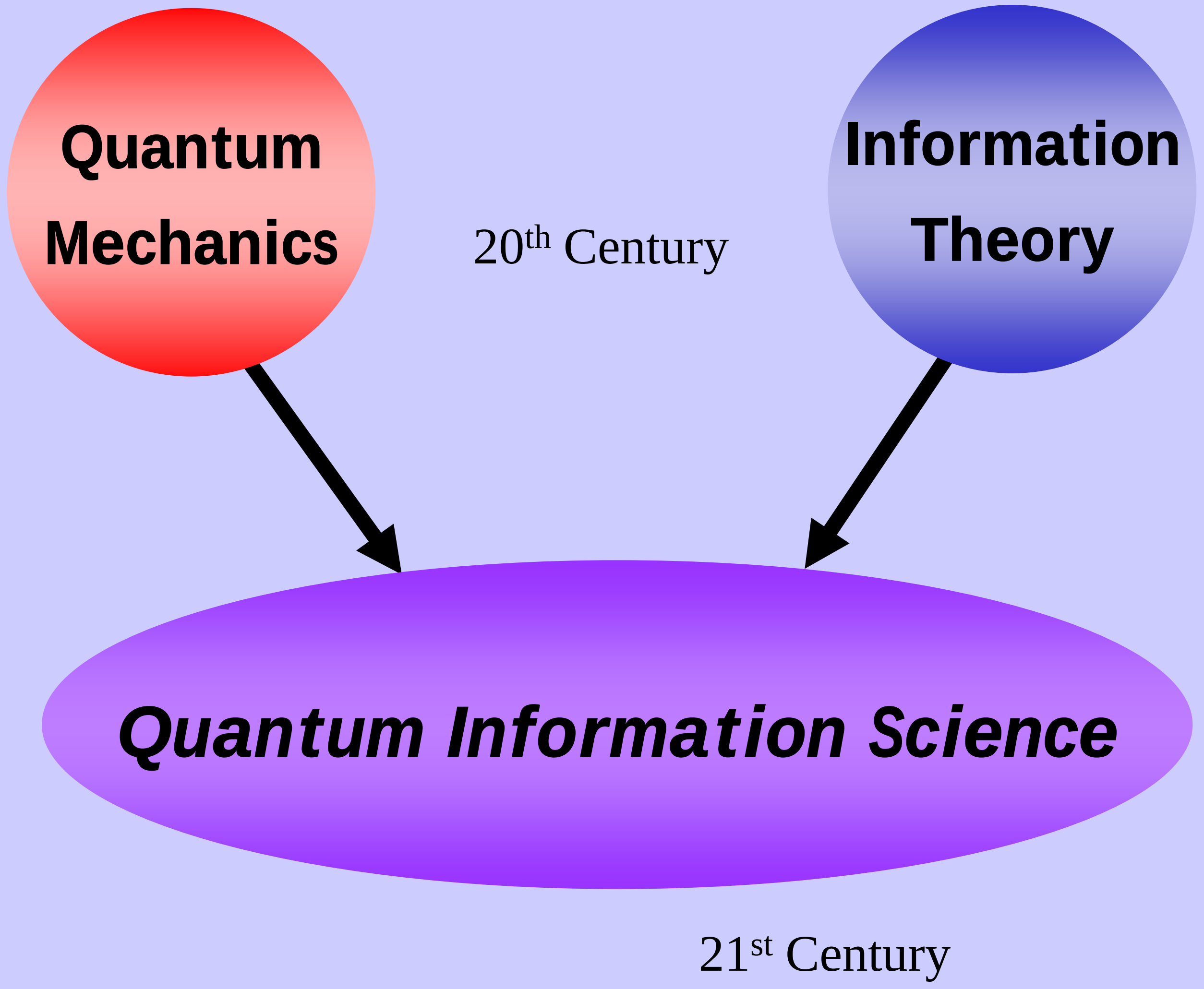
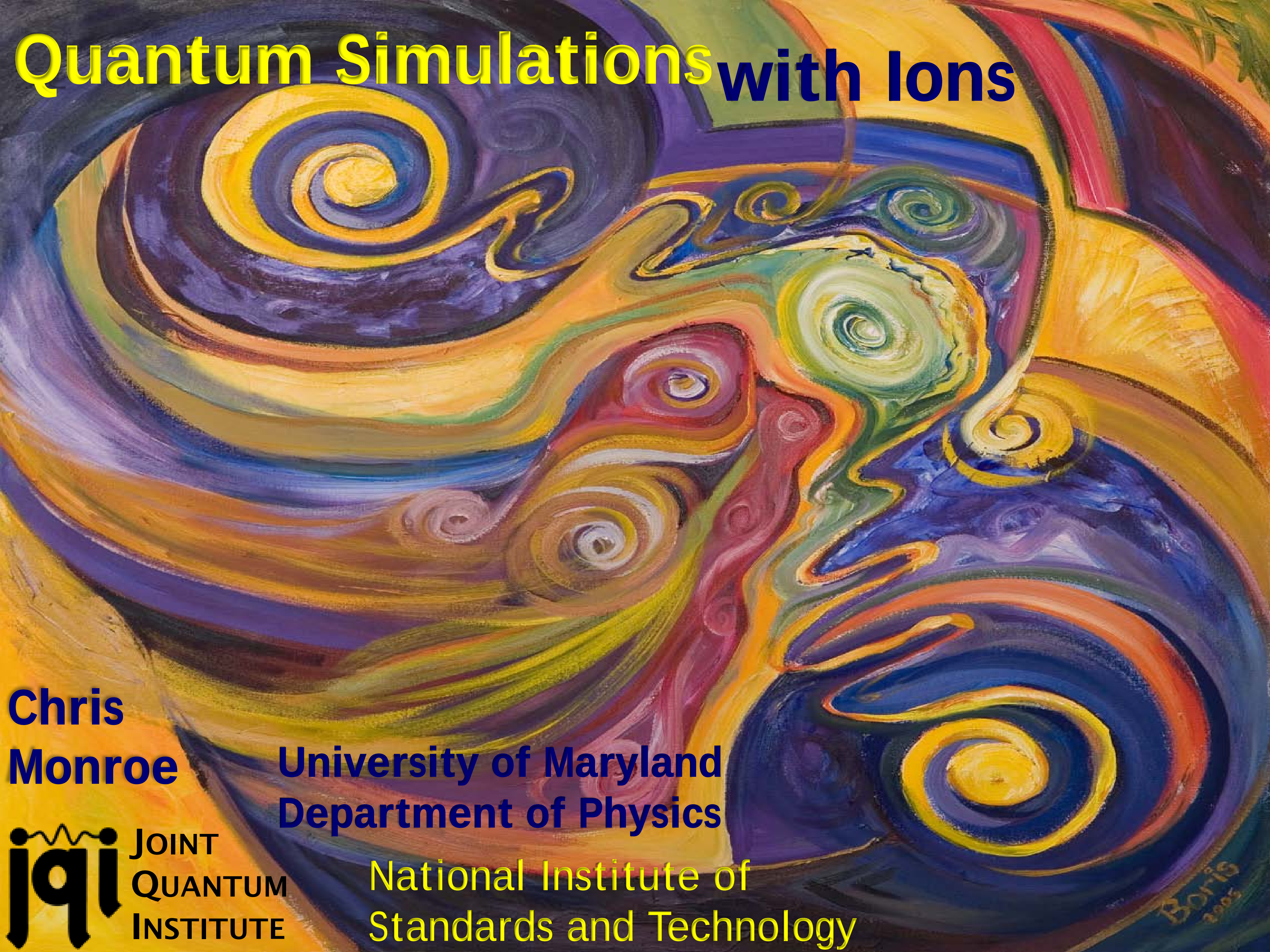
Michigan Summer Symposia: 1928-1941

Michigan Summer Symposia: 2008-

A new science for the 21st Century?



Quantum Simulations with Ions



Chris Monroe

University of Maryland
Department of Physics

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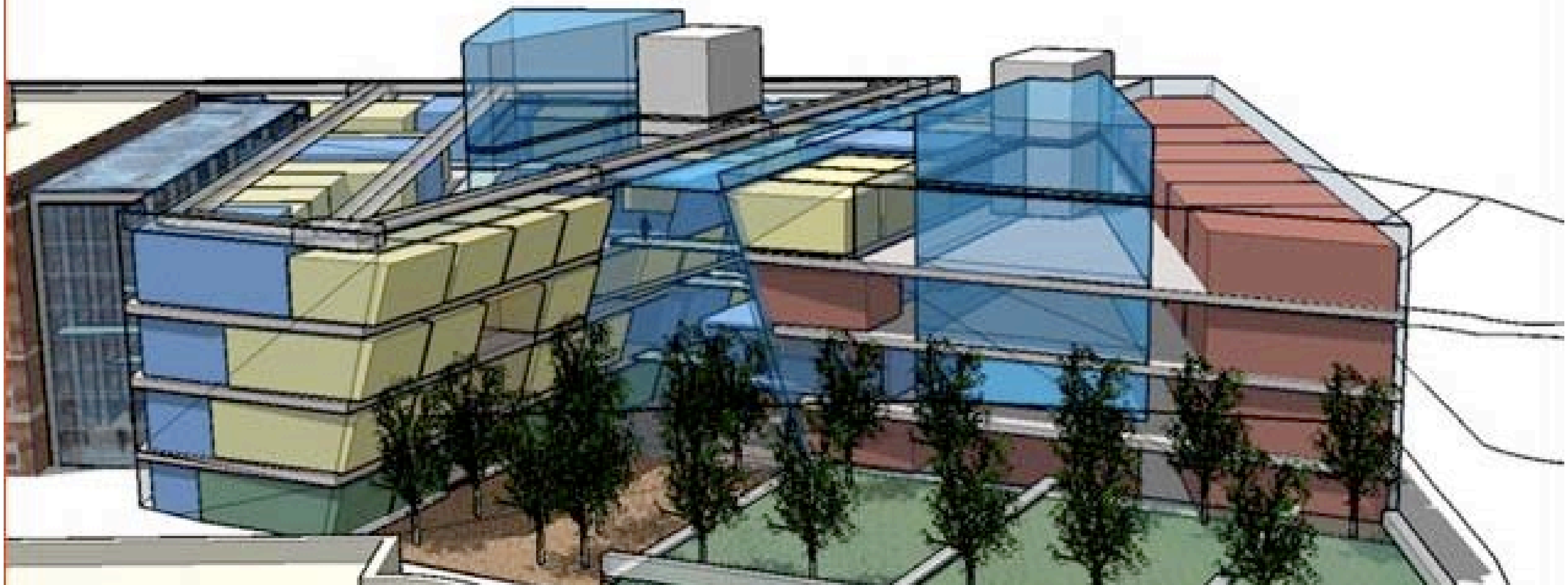
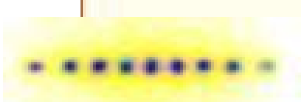
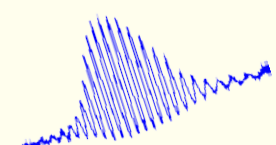
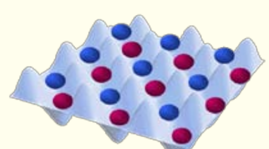
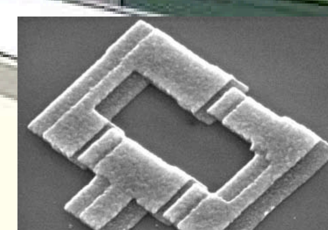


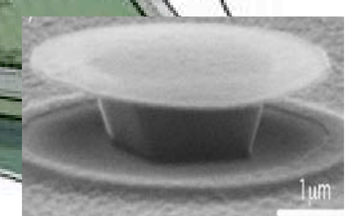
Quantum science for tomorrow's technology











Quantum Simulation: What is it?

$$i\hbar \frac{d\Psi}{dt} = H\Psi$$

Ψ Describes N interacting systems, each system having D degrees of freedom

D^N coupled differential equations

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

Two approaches

(1) Physical System Ψ $\longrightarrow$ Trial H $\longrightarrow$ $i\hbar \frac{d\Psi}{dt} = H\Psi$

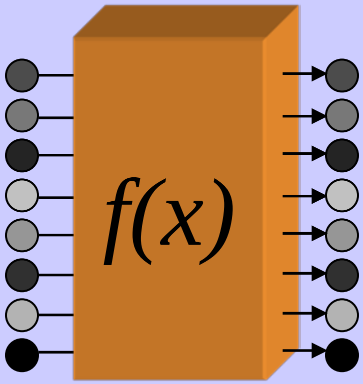
(2) Choose H $\longrightarrow$ Physical System Ψ $\longrightarrow$ $i\hbar \frac{d\Psi}{dt} = H\Psi$

Quantum Computing:

parallel processing on 2^N inputs

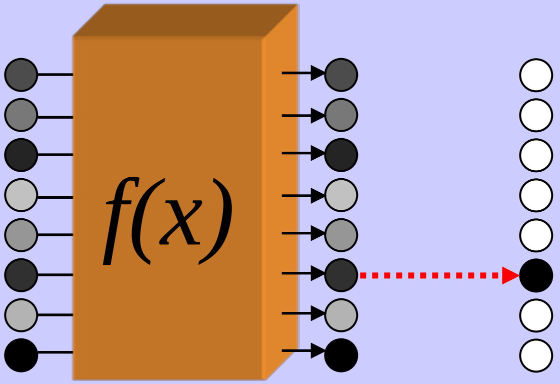
Example: N=3 qubits

$$\Psi = a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle$$
$$a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle$$

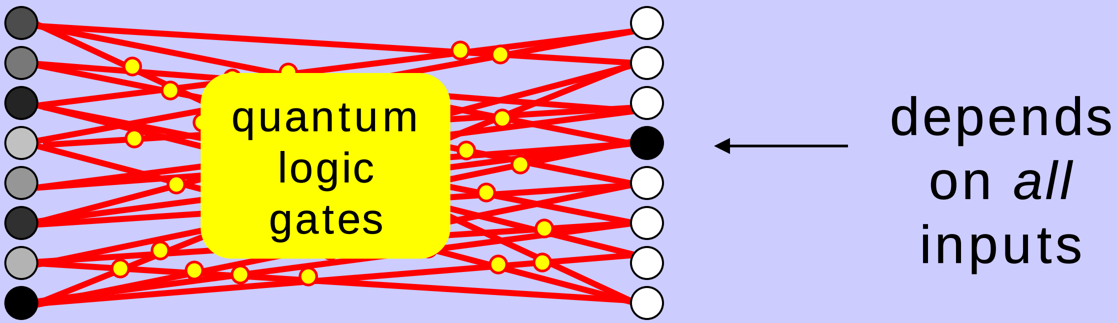


Measurement gives random result

e.g., $\Psi \Rightarrow |101\rangle$



quantum interference saves the day!

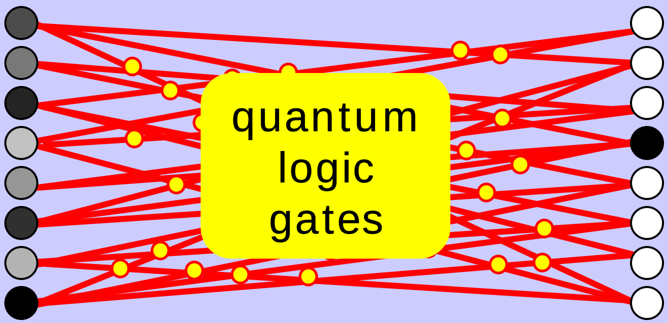


Deutsch (1985)

Shor (1994) fast number factoring $N = p \times q$

Grover (1996) fast database search

quantum interference saves the day!



depends on *all* inputs

quantum $\sqrt{\text{NOT}}$ gate:

$|0\rangle \rightarrow |0\rangle + |1\rangle$

$|1\rangle \rightarrow |1\rangle - |0\rangle$

quantum XOR gate:

$|0\rangle\,|0\rangle \rightarrow |0\rangle\,|0\rangle$

$|0\rangle\,|1\rangle \rightarrow |0\rangle\,|1\rangle$

$|1\rangle\,|0\rangle \rightarrow |1\rangle\,|1\rangle$

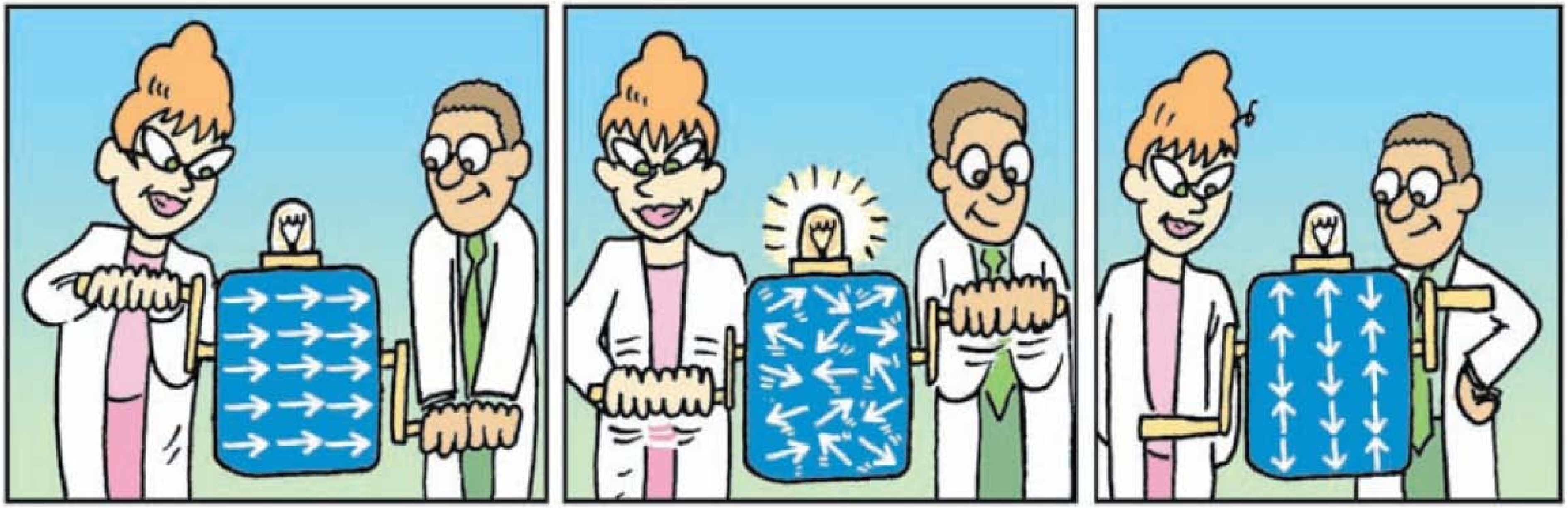
$|1\rangle\,|1\rangle \rightarrow |1\rangle\,|0\rangle$

e.g., $\left(|0\rangle + |1\rangle\right)|0\rangle \rightarrow |0\rangle|0\rangle + |1\rangle|1\rangle$

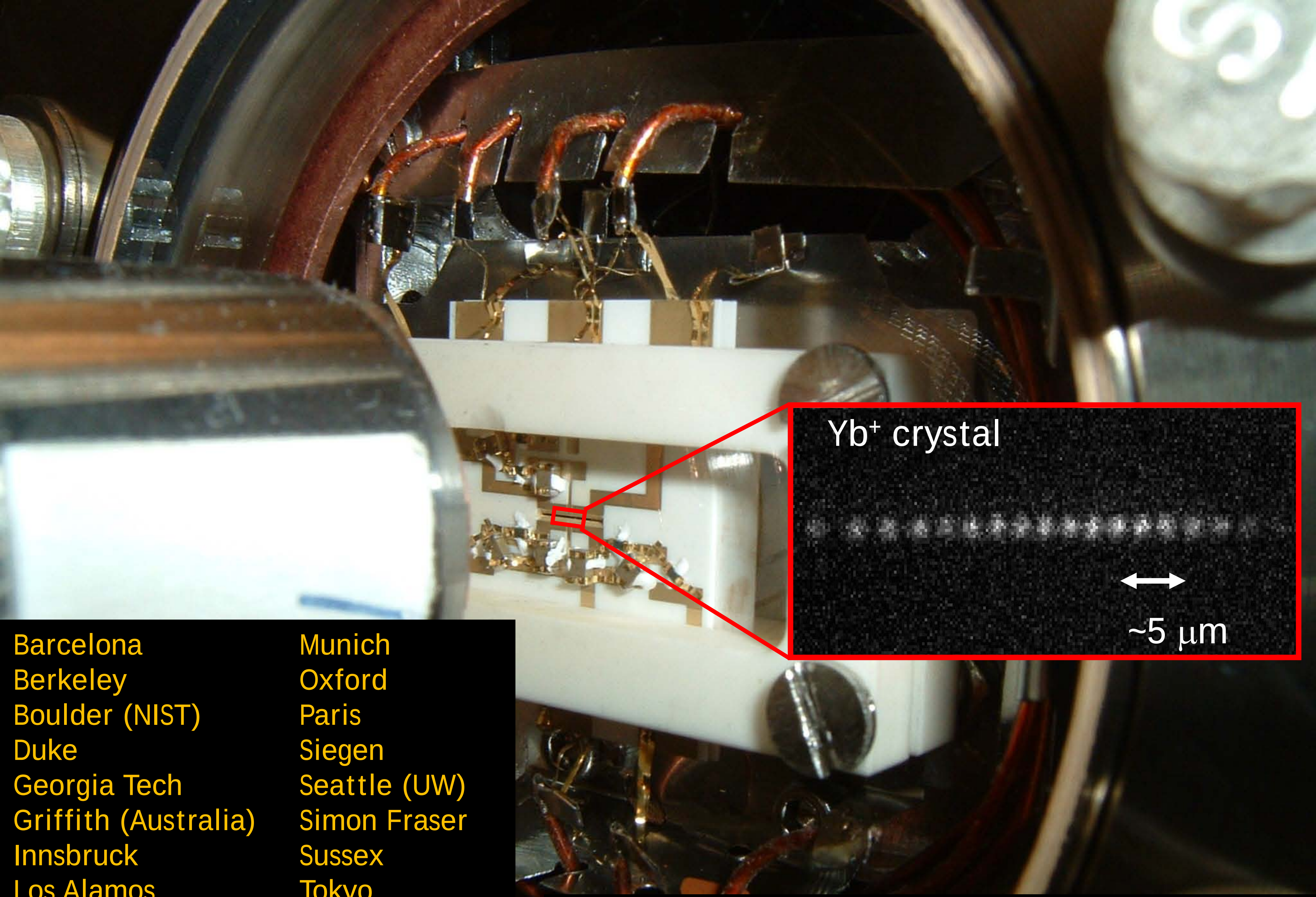
superposition → ***entanglement***

Quantum simulations with individual atoms

D. Porras and J. I. Cirac, *Phys. Rev. Lett.* **92**, 207901 (2004)
X.-L. Deng, D. Porras, and J. I. Cirac, *Phys. Rev.* **A 72**, 063407 (2005)
A. Friedenauer, et al., *Nature Physics* **4**, 757 (2008)
K. Kim, et al., *Phys. Rev. Lett.* **103**, 120502 (2009)
K. Kim, et al., *Nature* **465**, 590 (2010)
E. Edwards, et al., Phys. Rev. B (2010); ArXiv 1005.4160



from S. Lloyd, Science **319**, 1209 (2008)



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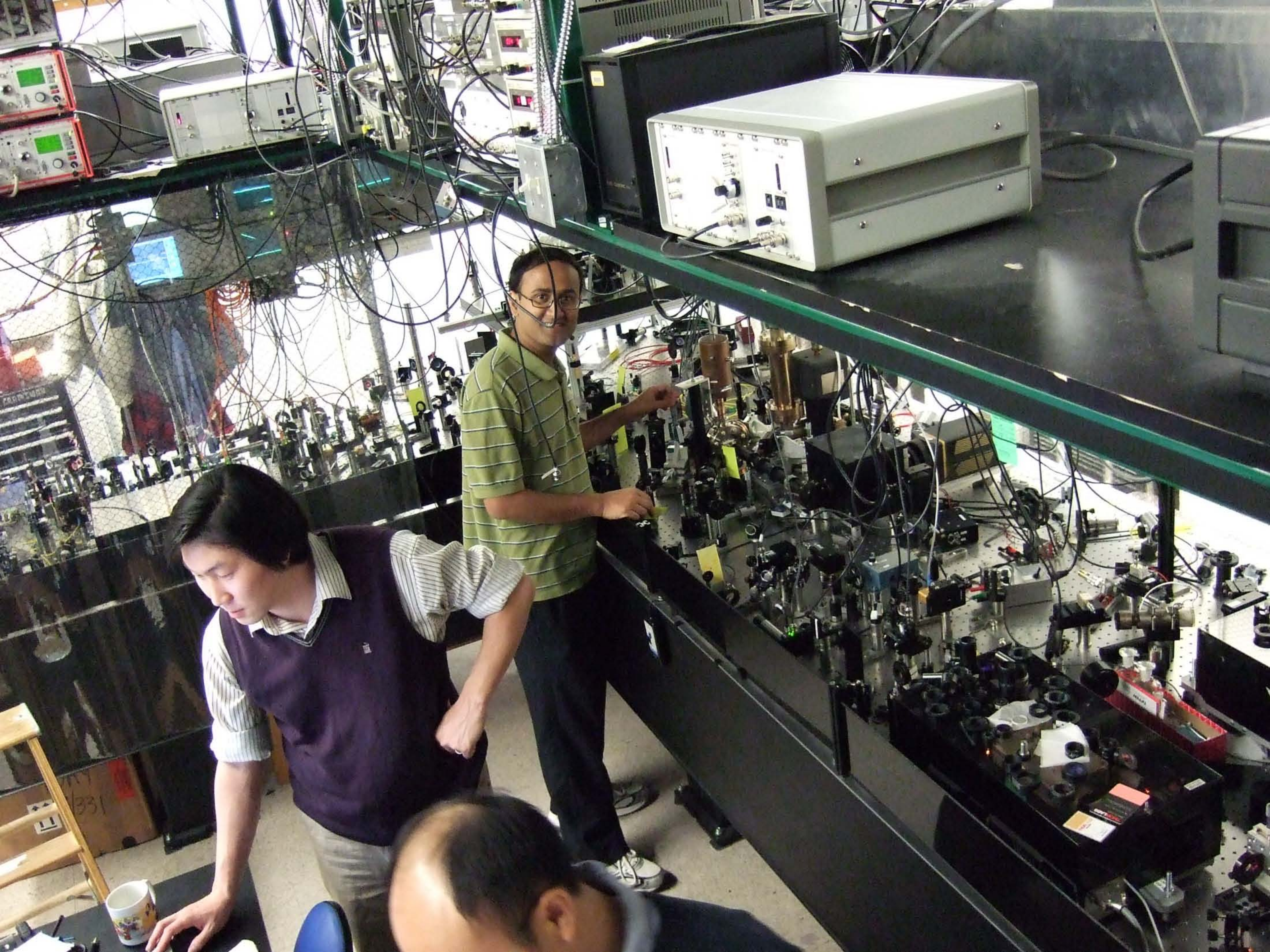
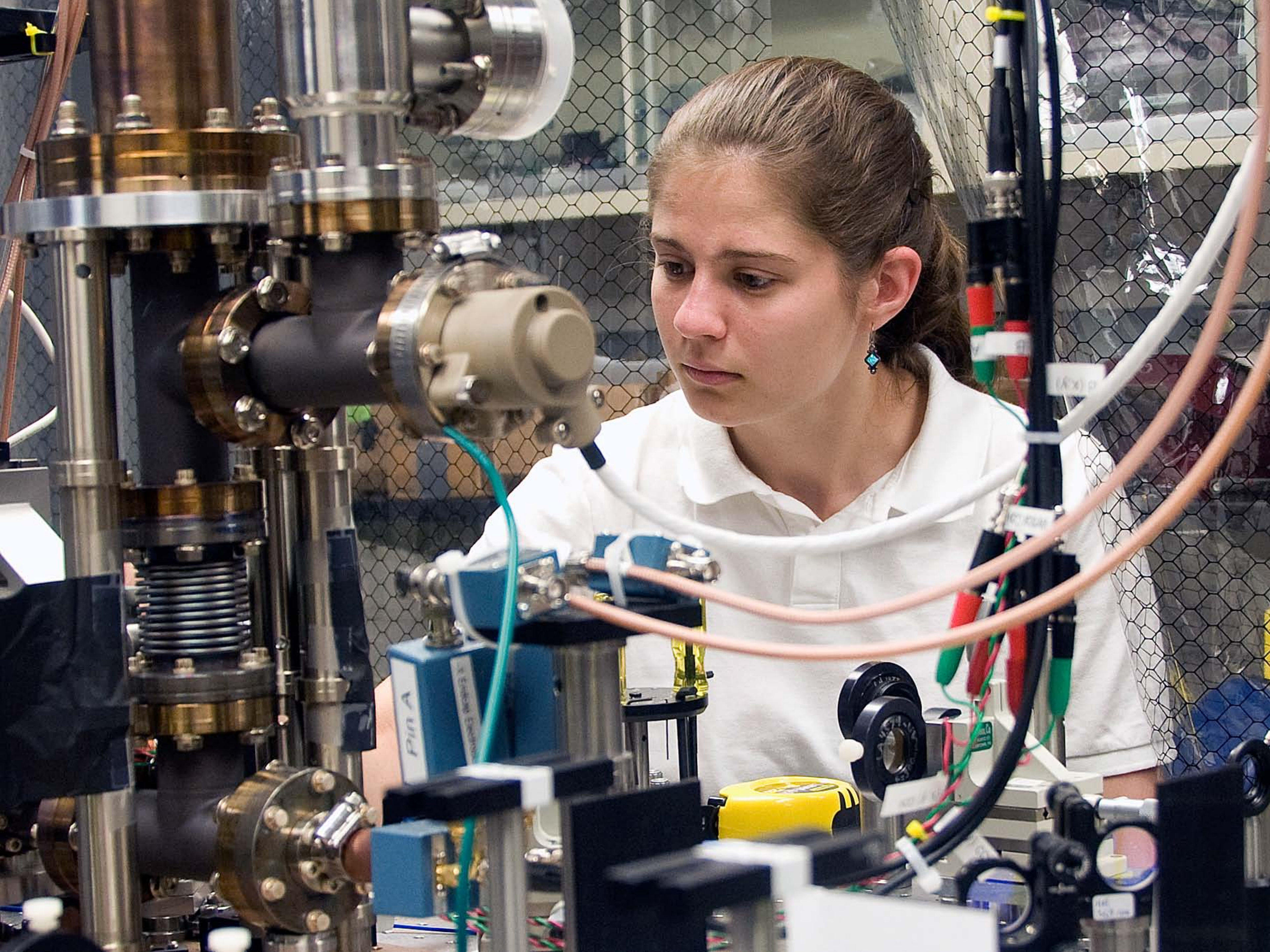
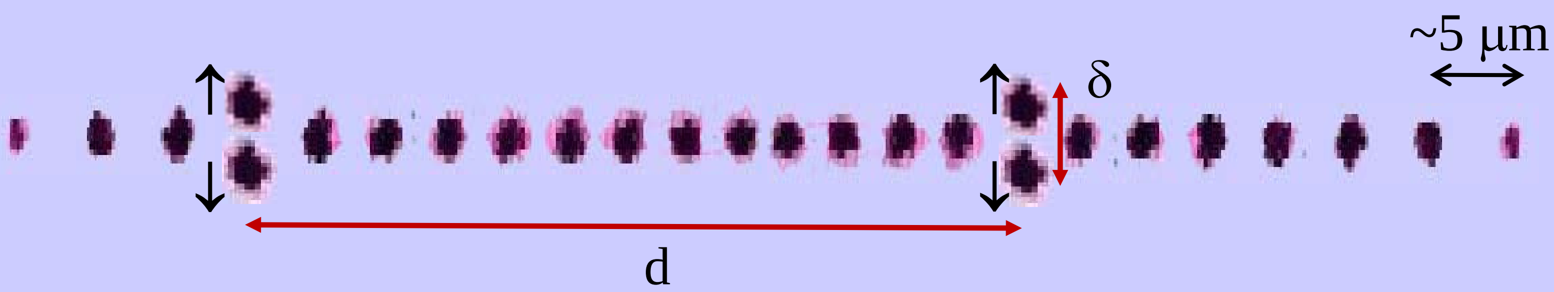
C.M. & D. J. Wineland, *Sci. Am.*, 64 (Aug 2008)
R. Blatt & D. J. Wineland, *Nature* **453**, 1008 (2008)




Pin A

Trapped Atomic Ions



spin-dependent force

$$F = F_0 |\uparrow\rangle\langle\uparrow| - F_0 |\downarrow\rangle\langle\downarrow|$$

Slow: Coulomb-coupled nonlocal normal modes, phonons

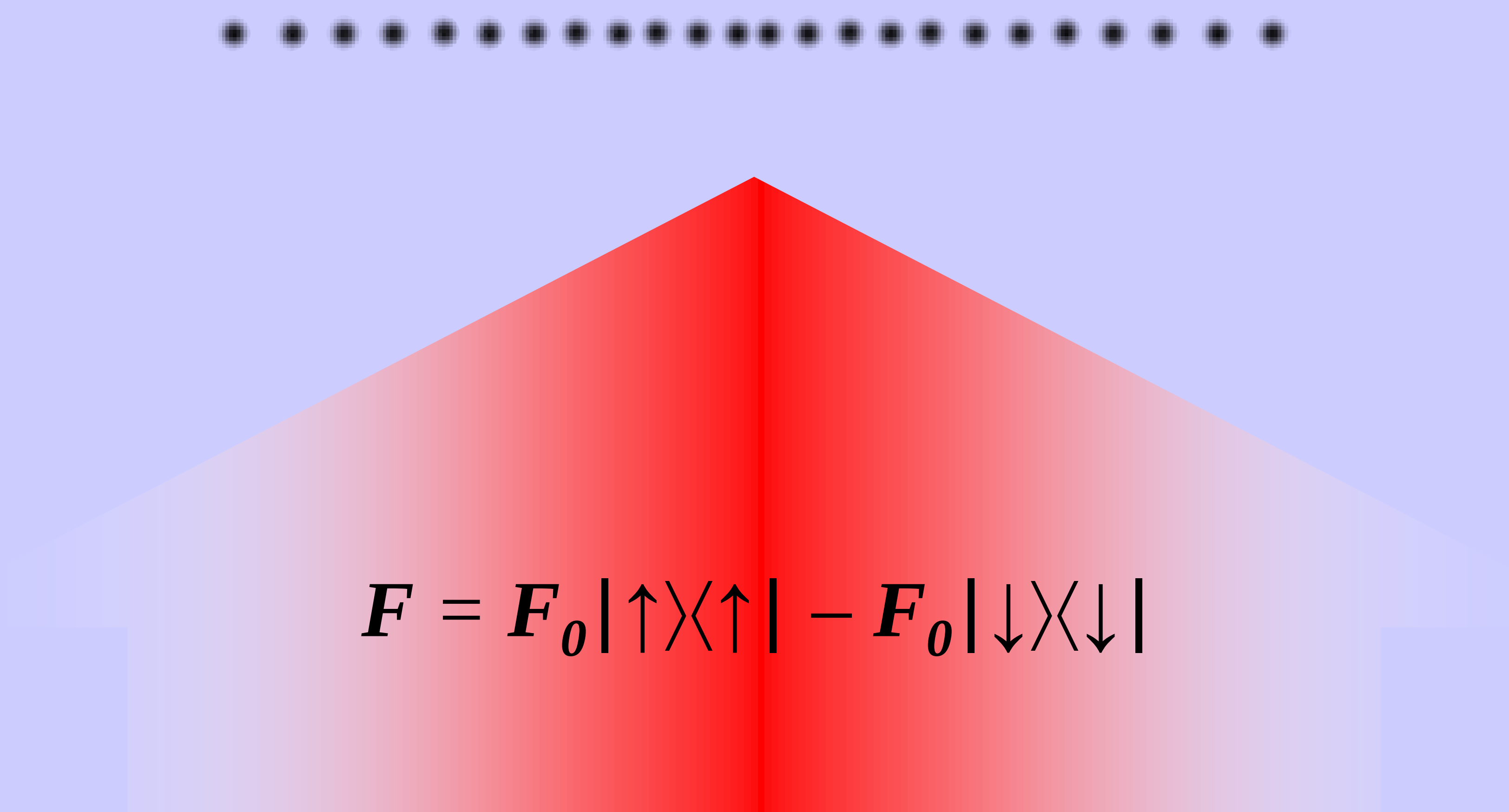
Fast: dipole-dipole coupling (or other forms)

$$\frac{e^2}{s} = \frac{e^2}{\sqrt{d^2+\delta^2}} = \frac{e^2}{d} - \frac{(e\delta)^2}{2d^3} + \ldots$$

$\delta \sim 20$ nm

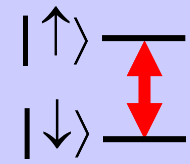
$e\delta \sim 1000$ Debye

Global spin-dependent force

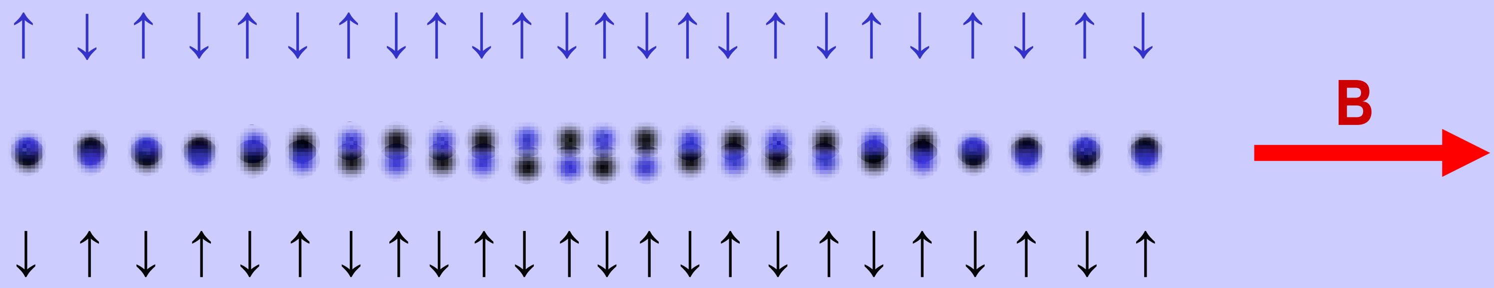


$$F = F_0 |\uparrow\rangle\langle\uparrow| - F_0 |\downarrow\rangle\langle\downarrow|$$

Global spin-dependent force



ADD: Independent spin flips



$$F = F_0|\uparrow\rangle\langle\uparrow| - F_0|\downarrow\rangle\langle\downarrow|$$

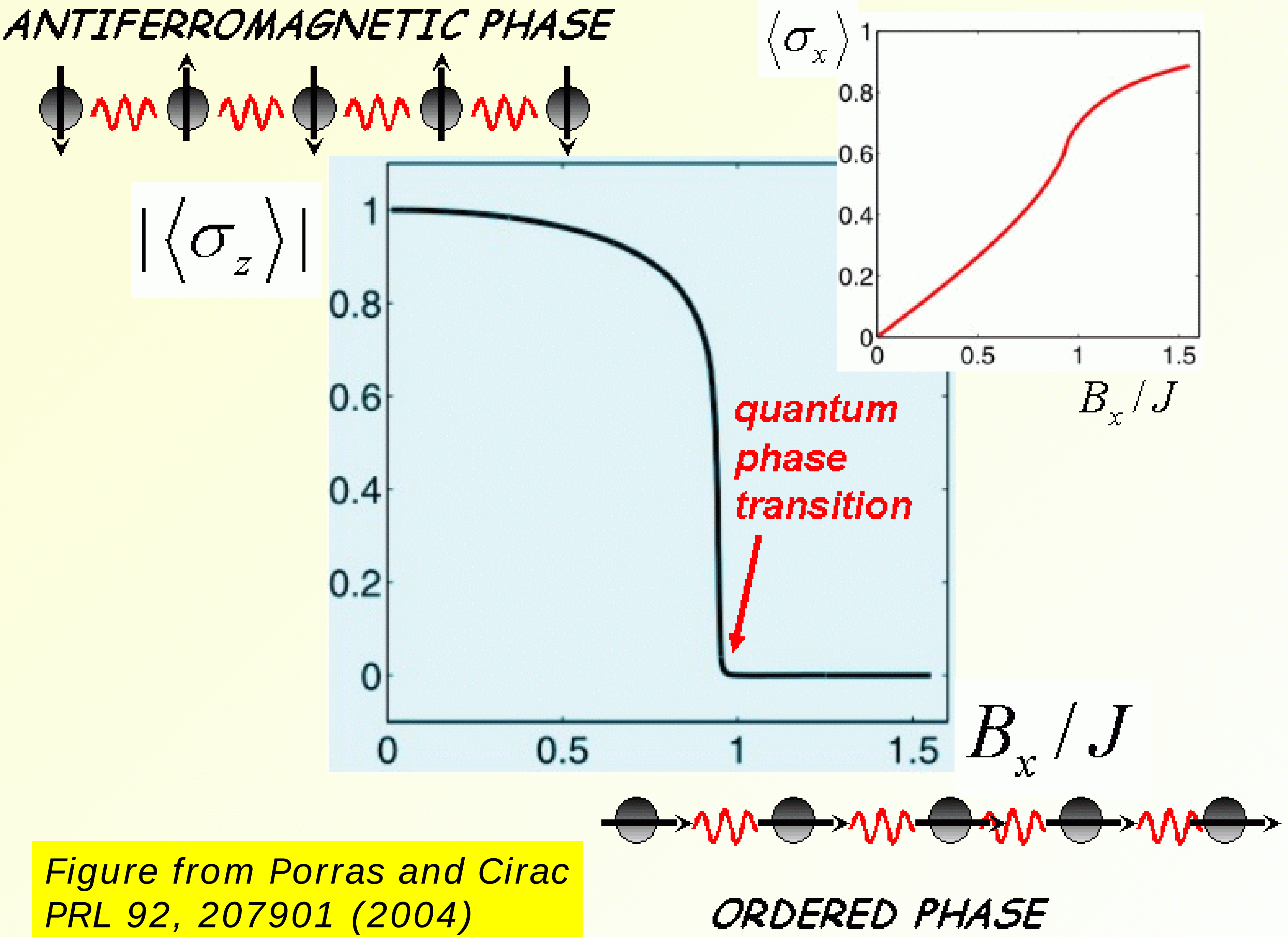


Figure from Porras and Cirac PRL 92, 207901 (2004)

Physics Laboratory physics.nist.gov | NIST www.nist.gov | Standard Reference Data Program www.nist.gov/srd

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

PERIODIC TABLE

Atomic Properties of the Elements

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ${}^{133}Cs$

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	$m_e c^2$	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,84 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

Period	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA	VIIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 ${}^2S_{1/2}$ **H** Hydrogen 1.00794 $1s$ 13.5984																	2 ${}^1S_0$ **He** Helium 4.00260 $1s^2$ 24.5874
2	3 ${}^2S_{1/2}$ **Li** Lithium 6.941 $1s^2 2s$ 5.3917	4 ${}^1S_0$ **Be** Beryllium 9.01218 $1s^2 2s^2$ 9.3227											5 ${}^2P^\circ_{1/2}$ **B** Boron 10.811 $1s^2 2s^2 2p$ 8.2980	6 ${}^3P_0$ **C** Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.2603	7 ${}^4S^\circ_{3/2}$ **N** Nitrogen 14.00674 $1s^2 2s^2 2p^3$ 14.5341	8 ${}^3P_2$ **O** Oxygen 15.9994 $1s^2 2s^2 2p^4$ 13.6181	9 ${}^2P^\circ_{3/2}$ **F** Fluorine 18.99840 $1s^2 2s^2 2p^5$ 17.4228	10 ${}^1S_0$ **Ne** Neon 20.1797 $1s^2 2s^2 2p^6$ 21.5646
3	11 ${}^2S_{1/2}$ **Na** Sodium 22.98977 [Ne]$3s$ 5.1391	12 ${}^1S_0$ **Mg** Magnesium 24.3050 [Ne]$3s^2$ 7.6462											13 ${}^2P^\circ_{1/2}$ **Al** Aluminum 26.98154 [Ne]$3s^2 3p$ 5.9858	14 ${}^3P_0$ **Si** Silicon 28.0855 [Ne]$3s^2 3p^2$ 8.1517	15 ${}^4S^\circ_{3/2}$ **P** Phosphorus 30.97376 [Ne]$3s^2 3p^3$ 10.4867	16 ${}^3P_2$ **S** Sulfur 32.066 [Ne]$3s^2 3p^4$ 10.3600	17 ${}^2P^\circ_{3/2}$ **Cl** Chlorine 35.4527 [Ne]$3s^2 3p^5$ 12.9676	18 ${}^1S_0$ **Ar** Argon 39.948 [Ne]$3s^2 3p^6$ 15.7596
4	19 ${}^2S_{1/2}$ **K** Potassium 39.0983 [Ar]$4s$ 4.3407	20 ${}^1S_0$ **Ca** Calcium 40.078 [Ar]$4s^2$ 6.1132	21 ${}^2D_{3/2}$ **Sc** Scandium 44.95591 [Ar]$3d4s^2$ 6.5615	22 ${}^3F_2$ **Ti** Titanium 47.867 [Ar]$3d^2 4s^2$ 6.8281	23 ${}^4F_{3/2}$ **V** Vanadium 50.9415 [Ar]$3d^3 4s^2$ 6.7462	24 ${}^7S_3$ **Cr** Chromium 51.9961 [Ar]$3d^5 4s$ 6.7665	25 ${}^6S_{5/2}$ **Mn** Manganese 54.93805 [Ar]$3d^5 4s^2$ 7.4340	26 ${}^5D_4$ **Fe** Iron 55.845 [Ar]$3d^6 4s^2$ 7.9024	27 ${}^4F_{9/2}$ **Co** Cobalt 58.93320 [Ar]$3d^7 4s^2$ 7.8810	28 ${}^3F_4$ **Ni** Nickel 58.6934 [Ar]$3d^8 4s^2$ 7.6398	29 ${}^2S_{1/2}$ **Cu** Copper 63.546 [Ar]$3d^{10} 4s$ 7.7264	30 ${}^1S_0$ **Zn** Zinc 65.39 [Ar]$3d^{10} 4s^2$ 9.3942	31 ${}^2P^\circ_{1/2}$ **Ga** Gallium 69.723 [Ar]$3d^{10} 4s^2 4p$ 5.9993	32 ${}^3P_0$ **Ge** Germanium 72.61 [Ar]$3d^{10} 4s^2 4p^2$ 7.8994	33 ${}^4S^\circ_{3/2}$ **As** Arsenic 74.92160 [Ar]$3d^{10} 4s^2 4p^3$ 9.7886	34 ${}^3P_2$ **Se** Selenium 78.96 [Ar]$3d^{10} 4s^2 4p^4$ 9.7524	35 ${}^2P^\circ_{3/2}$ **Br** Bromine 79.904 [Ar]$3d^{10} 4s^2 4p^5$ 11.8138	36 ${}^1S_0$ **Kr** Krypton 83.80 [Ar]$3d^{10} 4s^2 4p^6$ 13.9996
5	37 ${}^2S_{1/2}$ **Rb** Rubidium 85.4678 [Kr]$5s$ 4.1771	38 ${}^1S_0$ **Sr** Strontium 87.62 [Kr]$5s^2$ 5.6949	39 ${}^2D_{3/2}$ **Y** Yttrium 88.90585 [Kr]$4d5s^2$ 6.2171	40 ${}^3F_2$ **Zr** Zirconium 91.224 [Kr]$4d^2 5s^2$ 6.6339	41 ${}^6D_{1/2}$ **Nb** Niobium 92.90638 [Kr]$4d^4 5s$ 6.7589	42 ${}^7S_3$ **Mo** Molybdenum 95.94 [Kr]$4d^5 5s$ 7.0924	43 ${}^6S_{5/2}$ **Tc** Technetium (98) [Kr]$4d^5 5s^2$ 7.28	44 ${}^5F_5$ **Ru** Ruthenium 101.07 [Kr]$4d^7 5s$ 7.3605	45 ${}^4F_{9/2}$ **Rh** Rhodium 102.90550 [Kr]$4d^8 5s$ 7.4589	46 ${}^1S_0$ **Pd** Palladium 106.42 [Kr]$4d^{10}$ 8.3369	47 ${}^2S_{1/2}$ **Ag** Silver 107.8682 [Kr]$4d^{10} 5s$ 7.5762	48 ${}^1S_0$ **Cd** Cadmium 112.411 [Kr]$4d^{10} 5s^2$ 8.9938	49 ${}^2P^\circ_{1/2}$ **In** Indium 114.818 [Kr]$4d^{10} 5s^2 5p$ 5.7864	50 ${}^3P_0$ **Sn** Tin 118.710 [Kr]$4d^{10} 5s^2 5p^2$ 7.3439	51 ${}^4S^\circ_{3/2}$ **Sb** Antimony 121.760 [Kr]$4d^{10} 5s^2 5p^3$ 8.6084	52 ${}^3P_2$ **Te** Tellurium 127.60 [Kr]$4d^{10} 5s^2 5p^4$ 9.0096	53 ${}^2P^\circ_{3/2}$ **I** Iodine 126.90447 [Kr]$4d^{10} 5s^2 5p^5$ 10.4513	54 ${}^1S_0$ **Xe** Xenon 131.29 [Kr]$4d^{10} 5s^2 5p^6$ 12.1298
6	55 ${}^2S_{1/2}$ **Cs** Cesium 132.90545 [Xe]$6s$ 3.8939	56 ${}^1S_0$ **Ba** Barium 137.327 [Xe]$6s^2$ 5.2117		72 ${}^3F_2$ **Hf** Hafnium 178.49 [Xe]$4f^{14} 5d^2 6s^2$ 6.8251	73 ${}^4F_{3/2}$ **Ta** Tantalum 180.9479 [Xe]$4f^{14} 5d^3 6s^2$ 7.5496	74 ${}^5D_0$ **W** Tungsten 183.84 [Xe]$4f^{14} 5d^4 6s^2$ 7.8640	75 ${}^6S_{5/2}$ **Re** Rhenium 186.207 [Xe]$4f^{14} 5d^5 6s^2$ 7.8335	76 ${}^5D_4$ **Os** Osmium 190.23 [Xe]$4f^{14} 5d^6 6s^2$ 8.4382	77 ${}^4F_{9/2}$ **Ir** Iridium 192.217 [Xe]$4f^{14} 5d^7 6s^2$ 8.9670	78 ${}^3D_3$ **Pt** Platinum 195.078 [Xe]$4f^{14} 5d^9 6s$ 8.9587	79 ${}^2S_{1/2}$ **Au** Gold 196.96655 [Xe]$4f^{14} 5d^{10} 6s$ 9.2255	80 ${}^1S_0$ **Hg** Mercury 200.59 [Xe]$4f^{14} 5d^{10} 6s^2$ 10.4375	81 ${}^2P^\circ_{1/2}$ **Tl** Thallium 204.3833 [Hg]$6p$ 6.1082	82 ${}^3P_0$ **Pb** Lead 207.2 [Hg]$6p^2$ 7.4167	83 ${}^4S^\circ_{3/2}$ **Bi** Bismuth 208.98038 [Hg]$6p^3$ 7.2856	84 ${}^3P_2$ **Po** Polonium (209) [Hg]$6p^4$ 8.417 ?	85 ${}^2P^\circ_{3/2}$ **At** Astatine (210) [Hg]$6p^5$	86 ${}^1S_0$ **Rn** Radon (222) [Hg]$6p^6$ 10.7485
7	87 ${}^2S_{1/2}$ **Fr** Francium (223) [Rn]$7s$ 4.0727	88 ${}^1S_0$ **Ra** Radium (226) [Rn]$7s^2$ 5.2784		104 ${}^3F_2$? **Rf** Rutherfordium (261) [Rn]$5f^{14} 6d^2 7s^2$? 6.0 ?	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (268)	110 **Uun** Ununnilium (269)	111 **Uuu** Unununium (272)	112 **Uub** Ununbium						

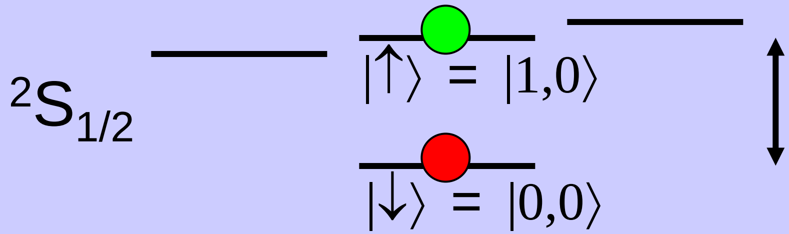
57 ${}^2D_{3/2}$ **La** Lanthanum 138.9055 [Xe]$5d6s^2$ 5.5769	58 ${}^1G^\circ_4$ **Ce** Cerium 140.116 [Xe]$4f5d6s^2$ 5.5387	59 ${}^4I^\circ_{9/2}$ **Pr** Praseodymium 140.90765 [Xe]$4f^3 6s^2$ 5.473	60 ${}^5I_4$ **Nd** Neodymium 144.24 [Xe]$4f^4 6s^2$ 5.5250	61 ${}^6H^\circ_{5/2}$ **Pm** Promethium (145) [Xe]$4f^5 6s^2$ 5.582	62 ${}^7F_0$ **Sm** Samarium 150.36 [Xe]$4f^6 6s^2$ 5.6436	63 ${}^8S^\circ_{7/2}$ **Eu** Europium 151.964 [Xe]$4f^7 6s^2$ 5.6704	64 ${}^9D^\circ_2$ **Gd** Gadolinium 157.25 [Xe]$4f^7 5d6s^2$ 6.1501	65 ${}^6H^\circ_{15/2}$ **Tb** Terbium 158.92534 [Xe]$4f^9 6s^2$ 5.8638	66 ${}^5I_8$ **Dy** Dysprosium 162.50 [Xe]$4f^{10} 6s^2$ 5.9389	67 ${}^4I^\circ_{15/2}$ **Ho** Holmium 164.93032 [Xe]$4f^{11} 6s^2$ 6.0215	68 ${}^3H_6$ **Er** Erbium 167.26 [Xe]$4f^{12} 6s^2$ 6.1077	69 ${}^2F^\circ_{7/2}$ **Tm** Thulium 168.93421 [Xe]$4f^{13} 6s^2$ 6.1843	70 ${}^1S_0$ **Yb** Ytterbium 173.04 [Xe]$4f^{14} 6s^2$ 6.2542	71 ${}^2D_{3/2}$ **Lu** Lutetium 174.967 [Xe]$4f^{14} 5d6s^2$ 5.4259
89 ${}^2D_{3/2}$ **Ac** Actinium (227) [Rn]$6d7s^2$ 5.17	90 ${}^3F_2$ **Th** Thorium 232.0381 [Rn]$6d^2 7s^2$ 6.3067	91 ${}^4K_{11/2}$ **Pa** Protactinium 231.03588 [Rn]$5f^2 6d7s^2$ 5.89	92 ${}^5L^\circ_6$ **U** Uranium 238.0289 [Rn]$5f^3 6d7s^2$ 6.1941	93 ${}^6L_{11/2}$ **Np** Neptunium (237) [Rn]$5f^4 6d7s^2$ 6.2657	94 ${}^7F_0$ **Pu** Plutonium (244) [Rn]$5f^6 7s^2$ 6.0262	95 ${}^8S^\circ_{7/2}$ **Am** Americium (243) [Rn]$5f^7 7s^2$ 5.9738	96 ${}^9D^\circ_2$ **Cm** Curium (247) [Rn]$5f^7 6d7s^2$ 5.9915	97 ${}^6H^\circ_{15/2}$ **Bk** Berkelium (247) [Rn]$5f^9 7s^2$ 6.1979	98 ${}^5I_8$ **Cf** Californium (251) [Rn]$5f^{10} 7s^2$ 6.2817	99 ${}^4I^\circ_{15/2}$ **Es** Einsteinium (252) [Rn]$5f^{11} 7s^2$ 6.42	100 ${}^3H_6$ **Fm** Fermium (257) [Rn]$5f^{12} 7s^2$ 6.50	101 ${}^2F^\circ_{7/2}$ **Md** Mendelevium (258) [Rn]$5f^{13} 7s^2$ 6.58	102 ${}^1S_0$ **No** Nobelium (259) [Rn]$5f^{14} 7s^2$ 6.65	103 ${}^2P^\circ_{1/2}$? **Lr** Lawrencium (262) [Rn]$5f^{14} 7s^2 7p$? 4.9 ?

Key: Atomic Number (58), Ground-state Level (${}^1G^\circ_4$), Symbol (Ce), Name (Cerium), Atomic Weight† (140.116), Ground-state Configuration ([Xe]$4f5d6s^2$), Ionization Energy (eV) (5.5387)

- Solids
- Liquids
- Gases
- Artificially Prepared

For a description of the atomic data, visit physics.nist.gov/atomic

$^{171}Yb^{+}$ hyperfine qubit



ν_{HF} = 12,642,812,118 + 311B^2 Hz

(3 kHz/G @ 5 G)