Precision Measurements with Trapped Ions

David Hume, Ion Storage Group, NIST



Precision Measurements with Trapped lons

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Internal quantum state control State preparation, detection and single-qubit gates with > 99.9% fidelity

Quantum-limited measurement precision

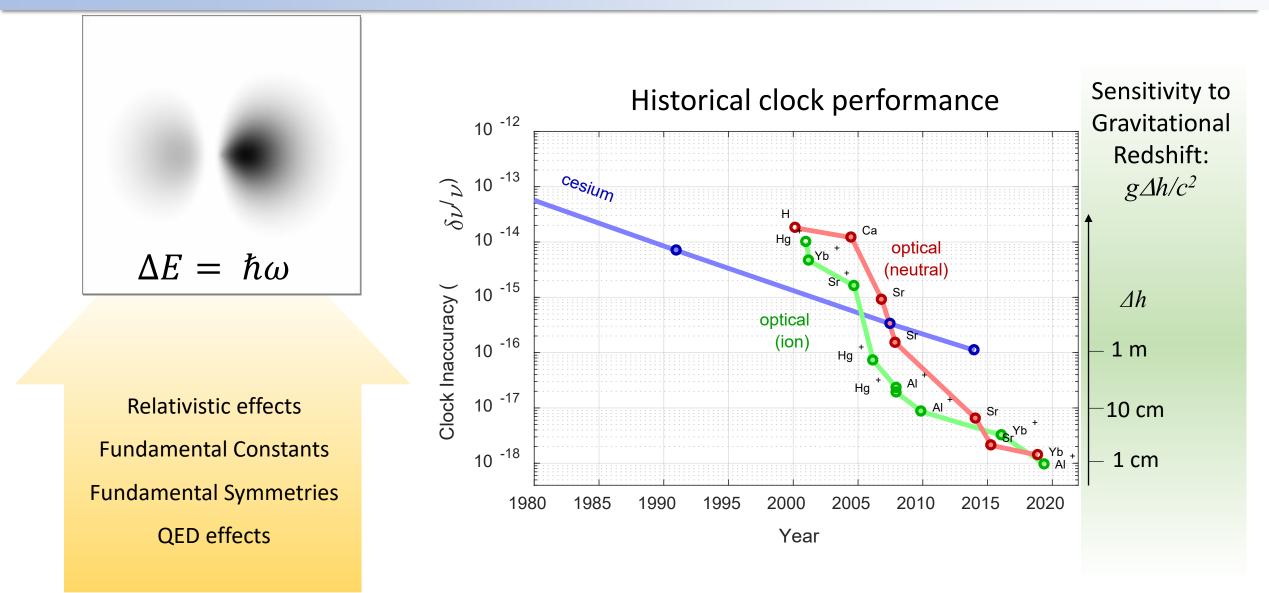
Long coherence times

~ 10 s at optical frequencies $Q > 10^{16}$

External quantum state control Cooling to the ground state of motion, heating rates ~ 1 quantum/s

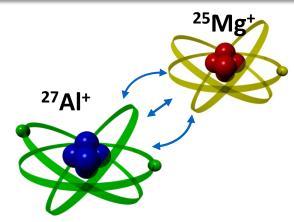
Strong, switchable interactions 2-qubit gates with >99.9% fidelity

Testing Fundamental Physics with Clocks



8/19/2020

Quantum Logic Spectroscopy



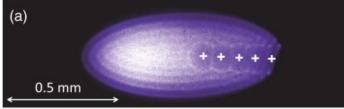
Other systems made accessible

Molecular ions, CaH⁺

+ nu *

Chou et al., Nature **545**, 203 (2017)





Schmoeger et al., Science **347**, 1233 (2015)

| | |

 | | cond = 9 192 6 | 31 770 periods of | ENTAL PHYSICAL CONSTANTS§
s of radiation corresponding to the
e levels of the ground state of ¹⁹³ Cs |
 | | |
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 | Physical Measurement Laboratory www.nist.gov/pml 2 1%
Standard Reference Data www.nist.gov/srd He | | | |
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| H
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1.008 2 | |

 | speed of light in | eed of light in vacuum | | 299 792 45
6.626 070 x | 8 m s ^{−1}
«10 ^{−34} J s
 | s ^{–1} (exact)
³⁴ Js | § For the most accurate
values of these and
other constants, visit |
 | |
 | | | | 17 | Helium
4.0026
 | |
| 15
13.5984
3 ² c | IIA |

 | | rge | е
те 2 | 9.109 384 | x 10 ⁻³¹ kg
 | | |
 | | IIIA
 | IVA | VA | VIA | VIIA | 24.5874
 | |
| Li | Be |

 | | onstant | m _e c
m _p
α | 1.672 622 > | x 10 ⁻²⁷ kg
 | | | Solids
Liquids
 | | В
 | C | N | 0 | F | Ne
 | |
| 6.94
15 ² 25 | 9.0122
15 ² 25 ² | R

 | tydberg consta | nt | R _m
R _m c | 3.289 841 9 | 960 x 10 ¹⁵ Hz
 | | | Gases
 | illy | 10.81
1s ² 2s ² 2p
 | 12.011
1s ² 2s ² 2p ² | 14.007
1s ² 2s ² 2p ³ | 18 ² 28 ² 2p ⁴ | 18.998
1s ² 2s ² 2p ⁵ | 20.180
1s ² 2s ² 2p ⁶
 | |
| 11 ² S _{1/2} | 12 ¹s₀ | -

 | | stant | R _∞ hc
eV
k | 1.602 177 > | x 10 ⁻¹⁹ J
 | | |
 | | 13 ² P ₁₂
 | 14 °P ₀ | 15 ⁴ S _{3/2} | 16 ³ P ₂ | 17 ² P ^o _{3/2} | 18 's,
 | |
| Sodium | Magnesium |

 | | | R | |
 | 0 | | 44
 | 10 | Aluminum
 | Silicon | Phosphorus | Sulfur | Chlorine | 100 C 100
 | |
| [Ne]3s
5.1391 | [Ne]3s ²
7.6462 | IIIB

 | IVB | VB | VIB | VIIB |
 | - VIII - | | IB
 | IIB | [Ne]35 ² 3p
5.9858
 | [Ne]3s ² 3p ²
8.1517 | [Ne]3s ² 3p ³
10.4867 | [Ne]35 ² 3p ⁴
10.3600 | [Ne]3s ² 3p ⁵
12.9676 | [Ne]3s ² 3p ⁶
15.7598
 | |
| 19 ² S _{1/2} | 20 's。
Ca | 21 ⁴⊃₃₂
SC

 | 22 ³ F ₂
Ti | 23 4F32
V | ²⁴ 's ₃
Cr | 25 ^s s ₂
Mn | 26 ⁵⊃₄
Fe
 | 27 ⁴⊧ ₉₂
Co | 28 ³⊧,
Ni | 29 ² S _{1/2}
Cu
 | 30 's
Zn | Ga
 | 32 ⁵₽.
Ge | 33 ⁴ 5 ₃₂
As | 34 ³₽,
Se | 35 ² P ₃₂
Br | 36 's₀
Kr
 | |
| Potassium
39.098 | Calcium
40.078 | Scandium
44.956

 | Titanium
47.867
(Art3d ² 4s ² | Vanadium
50.942 | Chromium
51.996
radiad ⁵ 4s | Manganese
54.938
(Art)3d ⁵ 4s ² | iron
55.845
 | Cobalt
58.933 | Nickel
58.693 | Copper
63.546
 | Zinc
65.38 | Gallium
69.723
(Ar13d ¹⁰ 4s ² 4n
 | Germanium
72.630 | Arsenic
74.922 | Selenium
78.971 | Bromine
79.904 | Krypton
83.798
 | |
| 4.3407
37 ² S _{1/2} | 6.1132
38 ¹ S ₀ | 6.5615

 | 6.8281
40 ³ F ₂ | 6.7462 | 42 ⁷ s ₃ | 7.4340
43 ⁶ S _{5/2} | ⁷ ,9025
44 ⁵ F ₅
 | 45 4F ₉₂ | 7.6399
46 ¹ S ₀ | 7.7264
47 ² S _{1/2}
 | 9.3942 | 5,9993
 | 7.8994
50 ³ P ₀ | 9.7886 | 9.7524
52 ³ P ₂ | 11.8138
53 ² P _{3/2} | 13.9996
54 ¹ S ₀
 | |
| Rubidium | Strontium | Yttrium

 | Zirconium | Nb
Niobium | Molybdenum | TC
Technetium | Ruthenium
 | Rhodium | Palladium | Ag
 | Cd
Cadmium | In
Indium
 | Tin | Sb
Antimony | Tellurium | lodine | Xe
Xenon
 | |
| [Kr]5s
4.1771 | 87.62
[Kr]5s ²
5.6949 | 88.906
[Kr]4d5s ²
6.2173

 | 91.224
[Kr]4d ² 5s ²
6.6341 | [Kr]4d ⁴ 5s
6.7589 | [Kr]4d ⁵ 5s
7.0924 | [Kr]4d 55 ²
7.1194 | [Kr]4d ⁷ 5s
7.3605
 | 102.91
[Kr]4d ⁸ 5s
7.4589 | 106.42
[Kr]4d ¹⁰
8.3369 | [Kr]4d ¹⁰ 5s
7.5762
 | 112.41
[Kr]4d ¹⁰ 5s ²
8.9938 |
 | | [Kr]4d ¹⁰ 5s ² 5p ³
8.6084 | 127.60
[Kr]4d ¹⁰ 5s ² 5p ⁴
9.0097 | [Kr]4d ¹⁰ 5s ² 5p ⁵
10.4513 | 131.29
[Kr]4d ¹⁰ 55 ² 5p ⁶
12.1298
 | |
| | 56 ¹s。
Ba |

 | 72 ³⊧₂
Hf | | 74 ⁵⊳₀
W | |
 | 77 ⁴ _{F92}
Ir | |
 | |
 | | | 84 ³ P ₂
PO | | 86 ¹ S ₀
 | |
| Cesium
132.91 | Barium
137.33 |

 | Hafnium
178.49 | Tantalum
180.95 | Tungsten
183.84 | Rhenium
186.21 | Osmium
190.23
 | Iridium
192.22 | Platinum
195.08 | Gold
196.97
 | Mercury
200.59 | Thallium
204.38
 | Lead
207.2 | Bismuth
208.98 | Polonium
(209) | Astatine
(210) | Radon
(222)
 | |
| | |

 | 6.8251 | 7.5496 | 7.8640 | 7.8335 | 8.4382
 | 8.9670 | 8.9588 | 9.2256
 | 10.4375 |
 | | 7.2855 | | |
 | |
| Fr | Ra | Ϋ́Ι.

 | Rf | Db | Sa | Bh | Hs
 | Mt | Ds | Rg
 | Cn | Nh
 | FI | Мс | Lv | Ts | Og
 | |
| (223) | (226) |

 | (267)
[Rn]5f ¹⁴ 6d ² 7s ² | (268)
[Rn]5f ¹⁴ 6d ³ 7s ² | [Rn]5f ¹⁴ 6d ⁴ 7s ² | (270)
[Rn]5f ¹⁴ 6d ⁵ 7s ² | (269)
[Rn]5f ¹⁴ 6d ⁶ 7s ²
 | (278) | (281) | (282)
 | (285) | (286)
 | (289) | (289) | (293) | (294) | (294)
 | |
| Atomic | Ground |

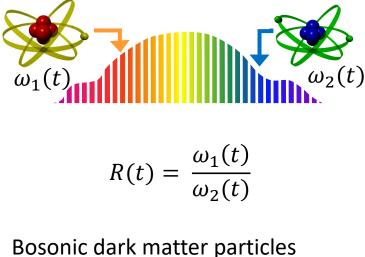
 | | | | |
 | 62 ⁷ E | 63 ªs* | 64 °D°
 | 65 ⁵ u° | 66 ⁵ 1
 | 67 41° | 68 ³ u | 69 ² c° | 70 ¹ s | 71 30
 | |
| Number | State | lanides

 | | Ce | Pr | Nd | Pm
 | Sm | Eu | Gd
 | Tb | Dy
 | Ho | Er | Tm | Yb | Lu
 | |
| /mbol | | Lanth

 | [Xe]5d6s ² | 140.116
[Xe]4f5d6s ² | 140.91
[Xe]4f ³ 6s ² | 144.24
[Xe]4f ⁴ 6s ² | (145)
IXe14f ⁵ 6s ²
 | 150.36
[Xe]4f ⁶ 6s ² | 151.96
[Xe]4f ⁷ 6s ² | 157.25
[Xe]4f ⁷ 5d6s ²
 | 158.93
[Xe]4f ⁹ 6s ² | [Xe]4f ¹⁰ 6s ²
 | 164.93
[Xe]4f ¹¹ 65 ² | 167.26
[Xe]4f ¹² 6s ² | 168.93
[Xe]4f ¹³ 6s ² | 173.05
[Xe]4f ¹⁴ 6s ² | 174.97
[Xe]4f ¹⁴ 5d6s ²
 | |
| -c | erium
40.12 |

 | 5.5769
89 ² D ₃₀ | 5.5388
90 ³ F ₂ | 5.4702
91_ ⁴ κ _{11/2} | <u>5.5250</u>
92 ໂ _ເ | 5.577
93 L _{11/2}
 | 5.6437
94 ⁷ F ₀ | 5.6704
95 ⁸ S _{7/2} |
 | 5.8638
97 ⁶ H ^o _{15/2} |
 | 6.0215
99 ⁴ I ^o ₁₅₂ | | 6.1843
101 ² F ^o _{7/2} | 6.2542
102 ¹ S ₀ |
 | |
| | 1.068
13.2684
3 2582
Li
Lihium
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3.3017
11 2512
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 -0.003 -0.003 <td< td=""><td>1008 2 13.5804 IIA 3 25.02 4 5.02 16 IIA 15.00 100.2017x 10⁻¹⁴ Jc 3 25.02 4 5.00 100.2017x 10⁻¹⁴ Jc 100.2017x 10⁻¹⁴ Jc 80.02 100.2017x 10⁻¹⁴ Jc 100.2017x 10⁻¹⁴ Jc 11 25.02 15.02 100.2017x 10⁻¹⁴ Jc 100.200 molecular 11 25.02 15.02 100.200 molecular 1107.000 molecular 20.0000 201.01 12 5.0017 111.75x2 12 5.0017 11 25.02 20 5.0017 20.500 00.00 molecular 1.0000 00.00 molecular 20.0000 244.00 72.12 15.000 00.00 molecular 1.0000 00.00 molecular 1.0000 00.00 molecular 21.01 72.12 20 5.000 00.00 molecular 1.0000 00.00 molecular 1.0000 00.00 molecular 21.01 72.12 72.12 72.17 72.17 72.17 72.17 72.17 72.17 72.17 72.17 72.17 72.17 72.17</td><td>1008 2 13.9580 IIA 3 2.522 II Secondari 3 2.524 III Secondari 3 2.524 III Secondari 11 2.527 11 2.527 11 2.527 11 2.527 11 2.527 11 2.527 11 2.527 11 2.527 11 2.527 11 2.527 11 2.527 11 2.527 12 2.527 13 2.4 5 13 2.4 5 13 2.4 5 13 2.4 7.5 14 5 6 7 8 9 113 2.4 7.5 2.5 5.2 1.5 2.5 5.6 13 2.5 5.2 1.5</td><td>1008 2 13.3080 2 13.3080 2 13.3080 2 13.3080 2 13.3080 2 13.3080 2 13.3080 2 13.3080 102 13.3080 102 13.3080 102 13.3080 102 13.3080 102 13.3080 102 13.3080 102 13.327 15.32 11.35x2 12.53 13.308 1118 13.308 3 4 5 13.308 3 4 5 111.35x2 12.53 12.55 22.62 15.4 111.10 1118 1118 1118 1118 1118 1119 1118 1118 1118 1118 1118 1118 1118 1118 1118 1118 1118 1118 1118 1118 1118 1118 1118<!--</td--><td>1008 2 13.058 2 13.058 2 14 15 3 25/sea 16 103.034 16 20.000 16 20.000 17 25/sea 16 24.000 16 24.000 17 25/sea 18 24.000 18 24.000 17 25/sea 18 24.000 24.000 56 24.000 56 24.000 56 25.000 56 26.000 56 21.000 56 21.000 56 21.000 56 21.0000 56 21.0000 20.000 21.0000 20.000 21.00000 21.00000 21.00000 21.00000 21.00000 21.00000 21.00000 21.00000 21.000000 21.00000</td><td>1008 2 103 3 3 5 5 5 5 6 7 7 107 20 107<td>100 2 100</td><td>1000
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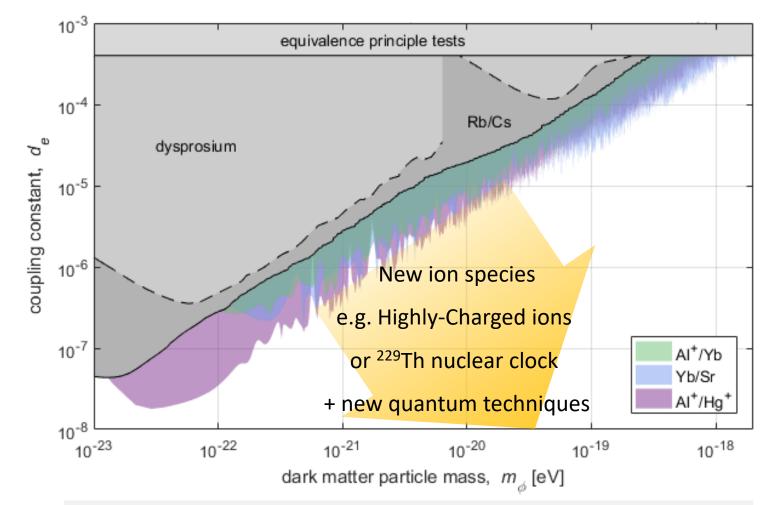
Searching for Ultralight Dark Matter



behave as a scalar field oscillating at the particle Compton frequency.

$$\omega_{DM} = \frac{m_{\phi}c^2}{\hbar}$$

Any coupling to SM fields would lead to an oscillation in the frequency ratio.



See also: Tilburg et al., PRL 115, 011802 (2015) and Hees et al., PRL 117, 061301 (2016)

8/19/2020

- Trapped ions are a leading platform for atomic clocks and quantum computing.
- Quantum information technology has already had a profound impact on sensing applications, making this platform an interesting case study for quantum sensors.
- The precision and accuracy of atomic clocks coupled with their sensitivity to effects in fundamental physics make them useful in a variety of tests of the standard model.

