Title: Single-atom Optical Clocks and Fundamental Constants

Date: Jul 16, 2008 02:40 PM

URL: http://pirsa.org/08070020

Abstract:

Single-atom Optical Clocks & Fundamental Constants

Jim Bergquist

Hg+ clock

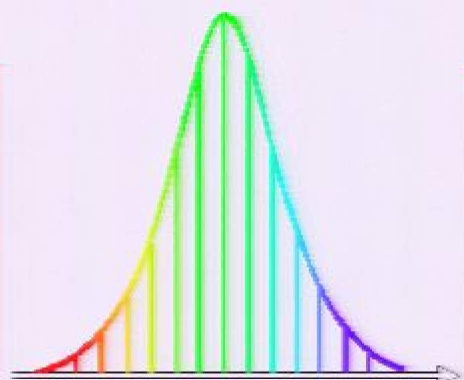
Windell Oskay
Anders Brusch
Luca Lorini
Wayne M. Itano
David J. Wineland

Al+ clock

Till Rosenband
David B. Hume
P. O. Schmidt
Wayne M. Itano
David J. Wineland

fs-comb (Ti:Sapphire)

Tara M. Fortier
Jason E. Stalnaker
Scott A. Diddams



fs-comb (fiber)

Ian Coddington
William C. Swann
Nate R. Newbury

ONR NIST DTO

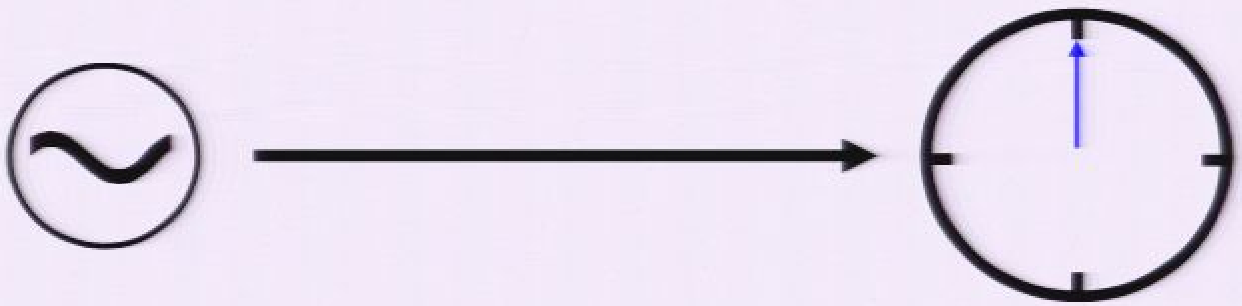
Outline

- Optical clocks
- Hg^+ and Al^+ clock transition spectroscopy
- Measurement of Al^+ / Hg^+ ratio
- Al^+ and Hg^+ systematic uncertainties
- 3-ion gymnastics
- Future plans

What is a clock?

An Oscillator
(Generates periodic events)

A Counter
(Count and display events / tell time)



Period Δt

Frequency $f = 1/\Delta t$

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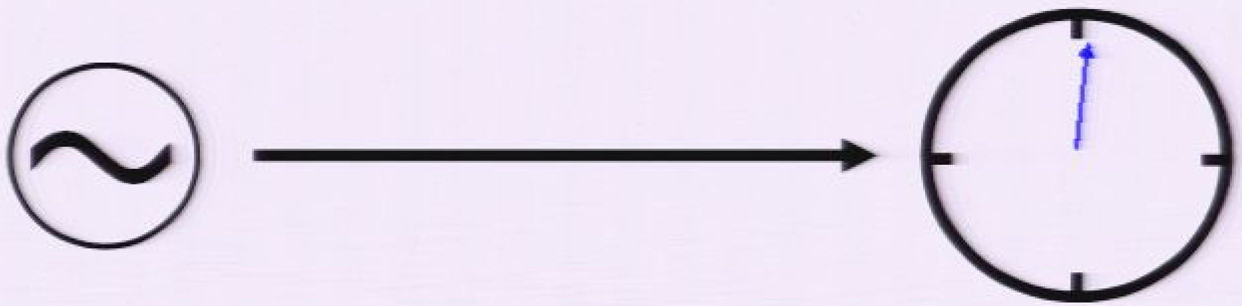

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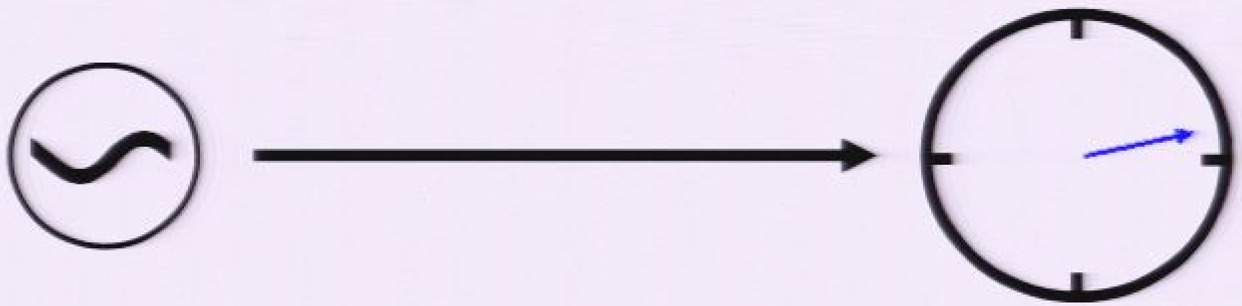

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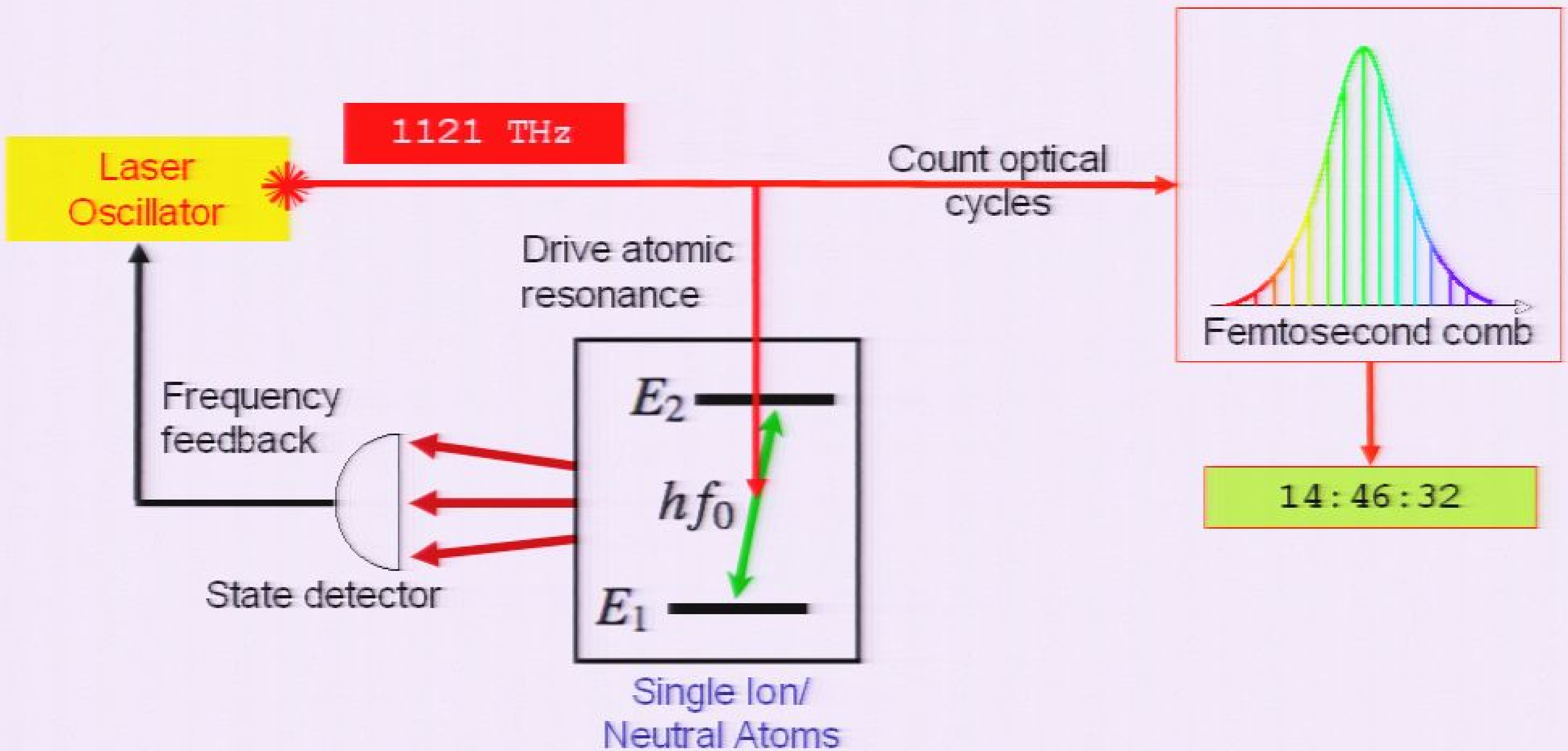
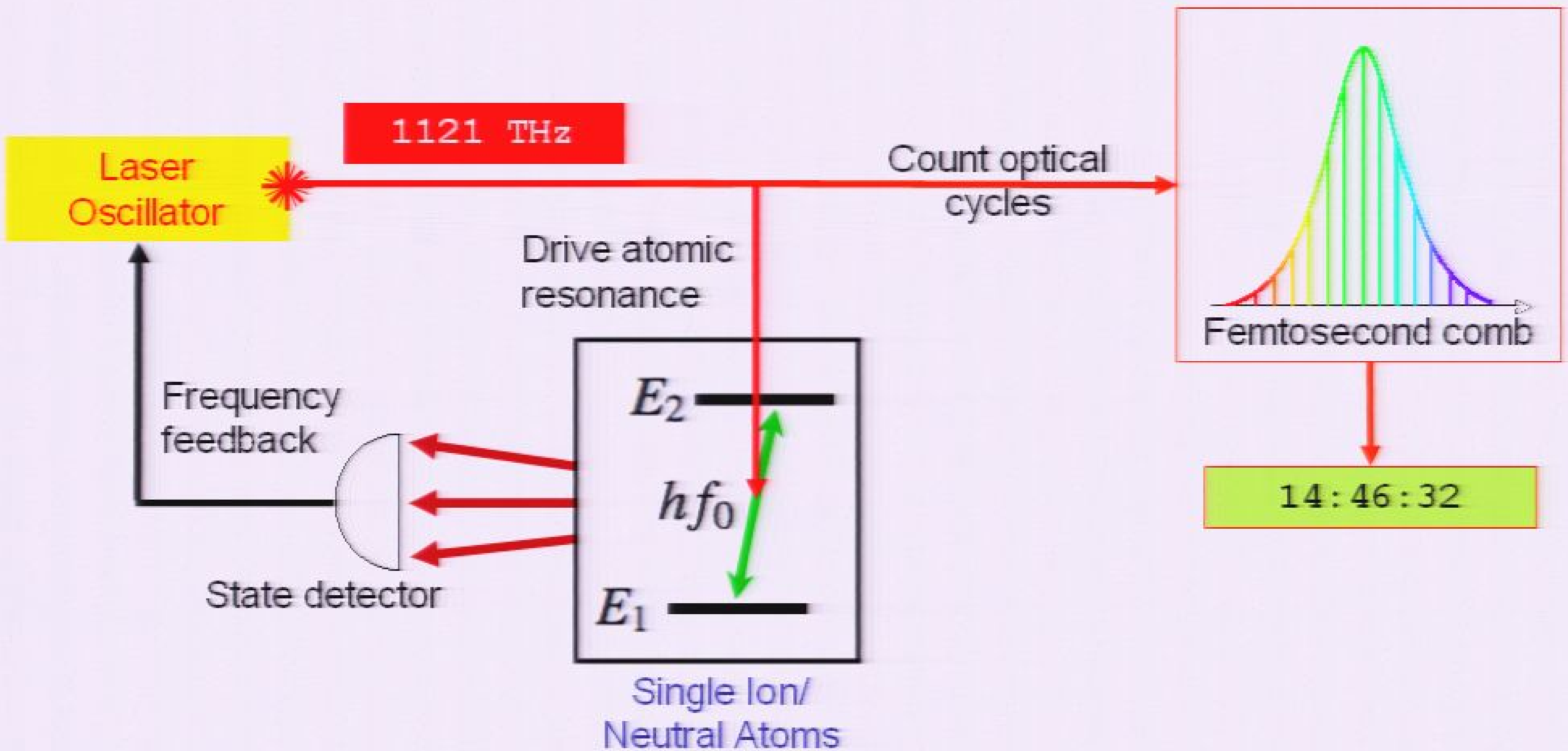
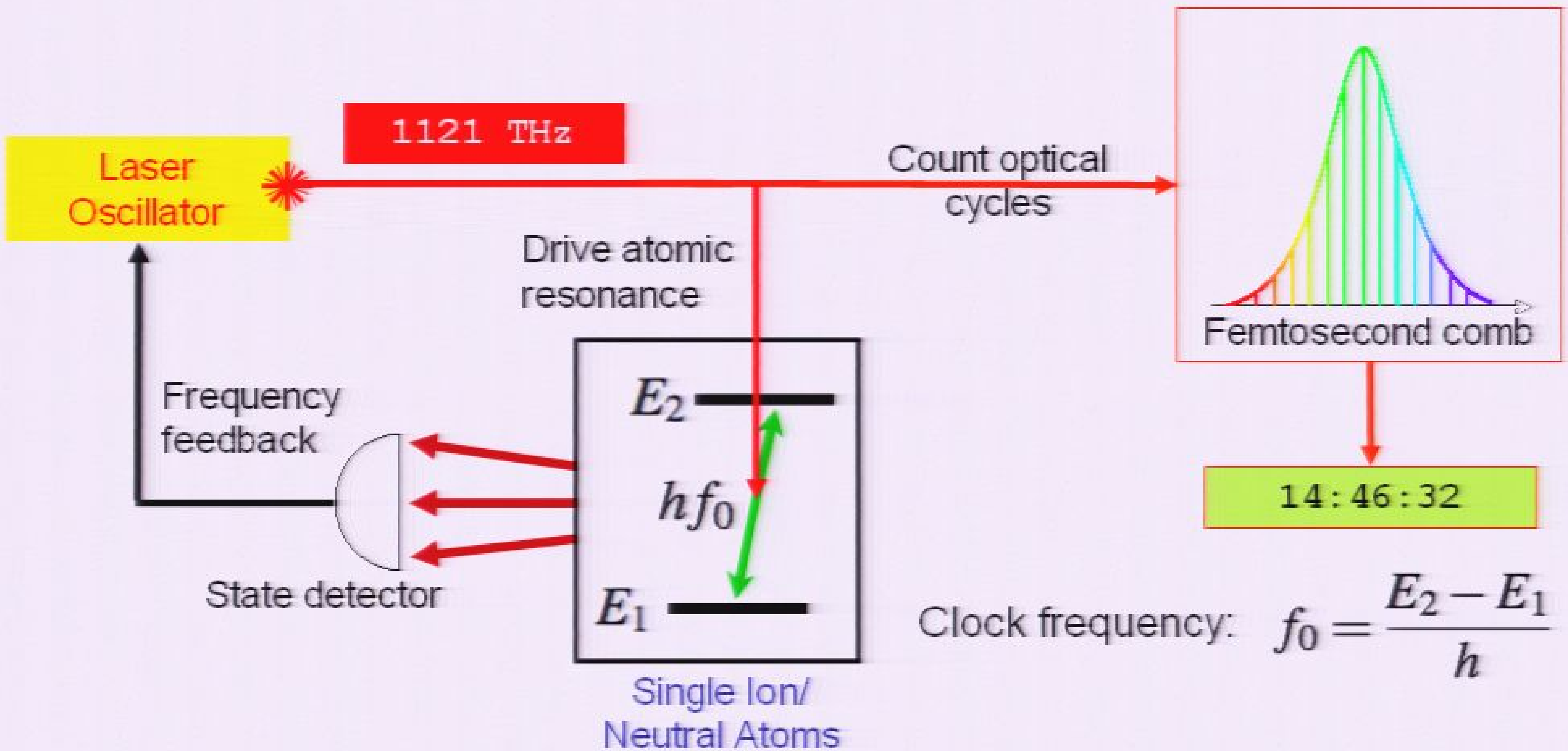
Optical Clock



Optical Clock

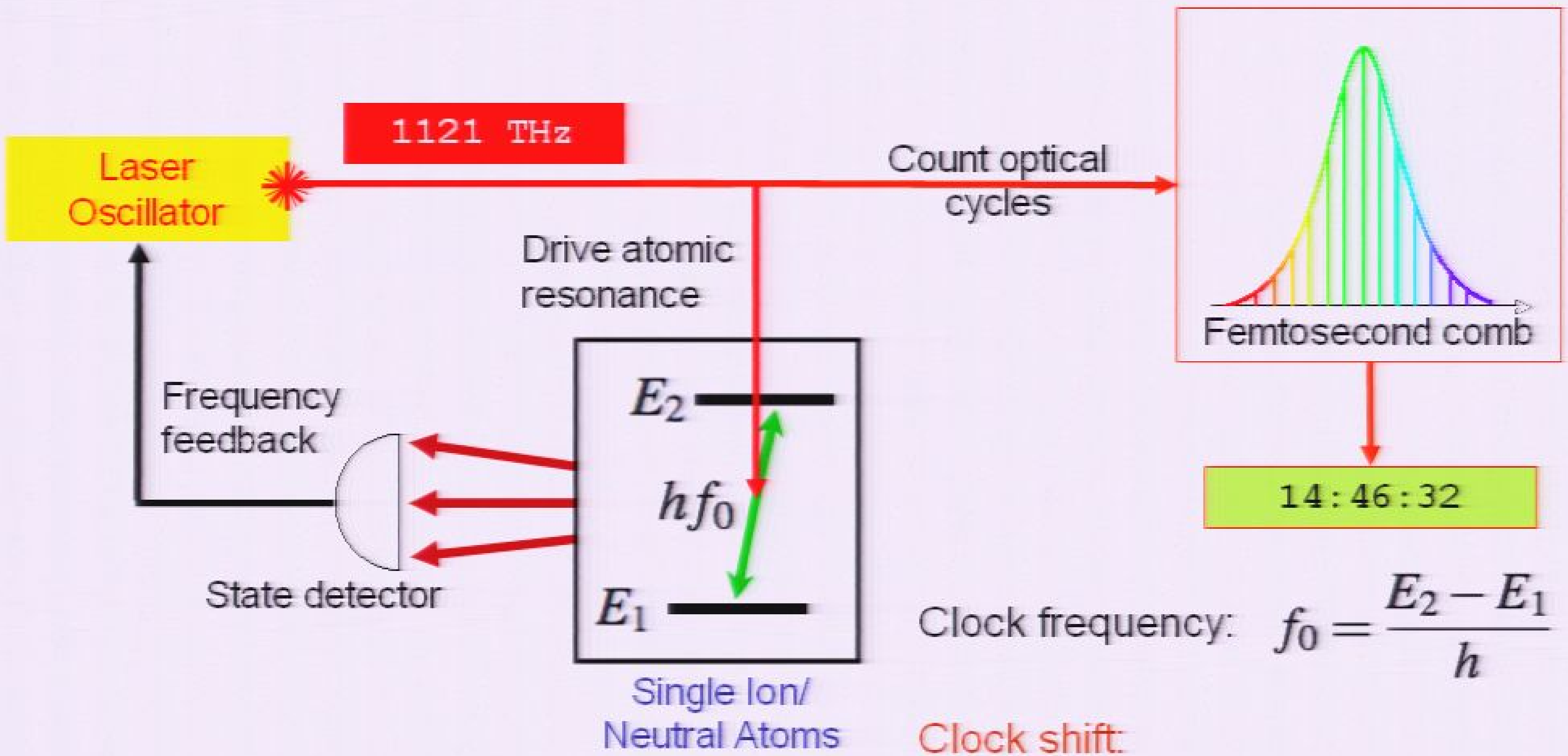


Optical Clock



Clock frequency: $f_0 = \frac{E_2 - E_1}{h}$

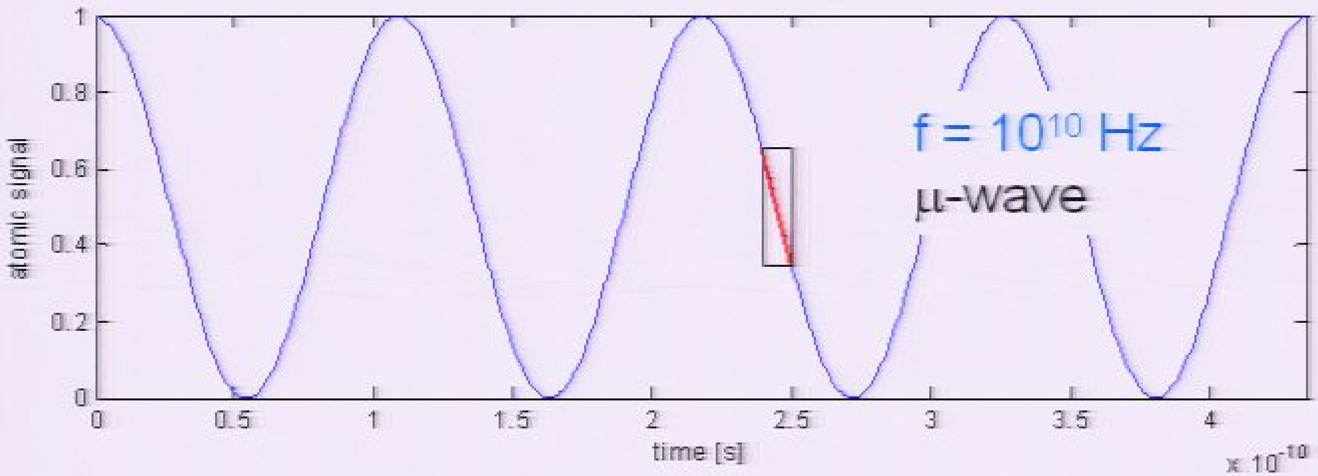
Optical Clock



Clock frequency: $f_0 = \frac{E_2 - E_1}{h}$

Clock shift:
anything that shifts (E_2-E_1)

Stability of microwave and optical atomic clocks (single measurement)



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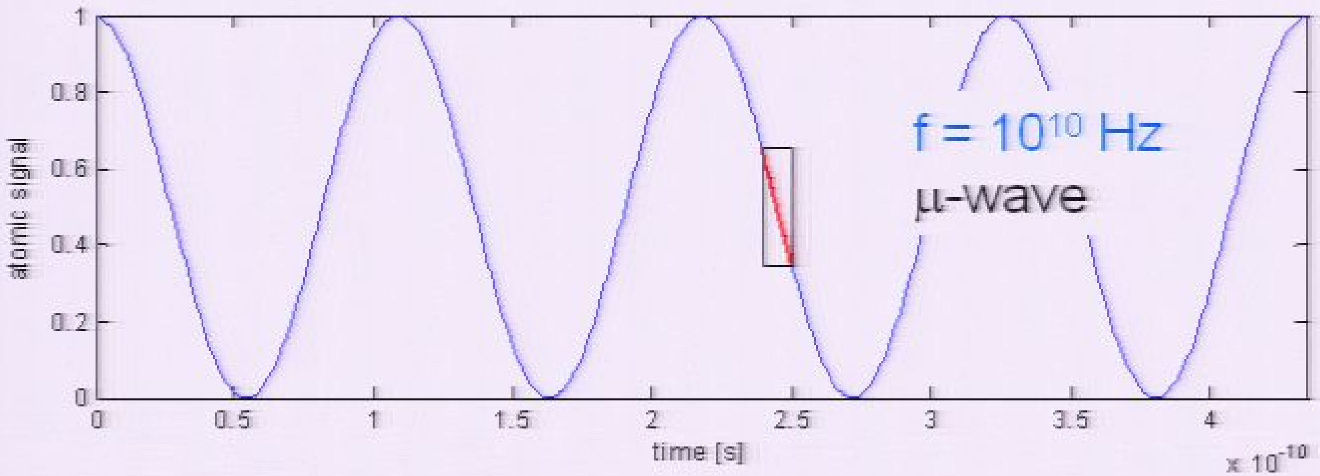

- Atomic reference oscillator

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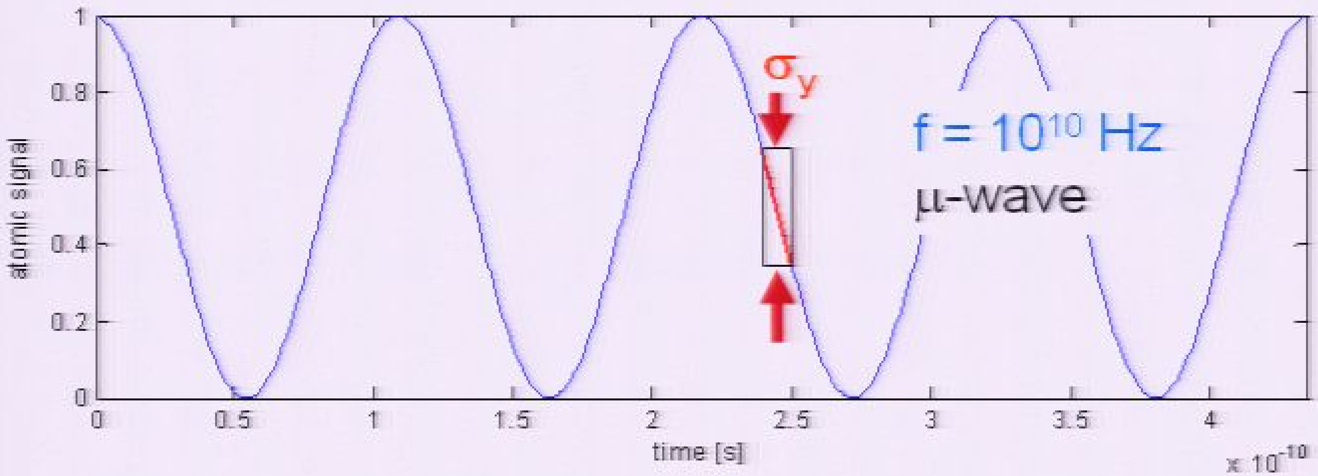

- Atomic reference oscillator
- time ~ phase of sinusoid
- Measurement error: σ_y

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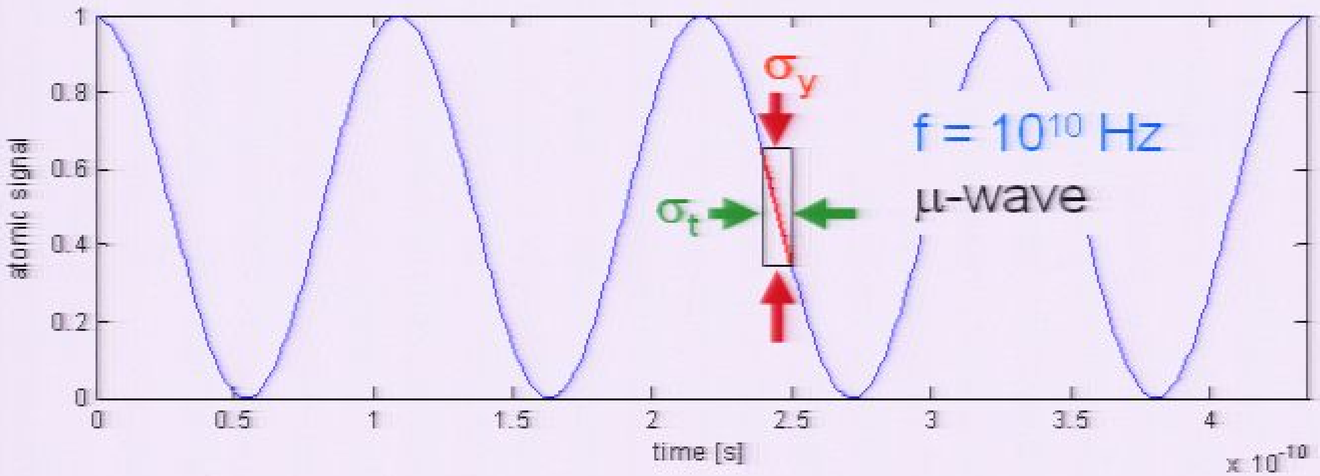

- Atomic reference oscillator
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- Time error: $\sigma_t = \sigma_y / (2\pi f)$

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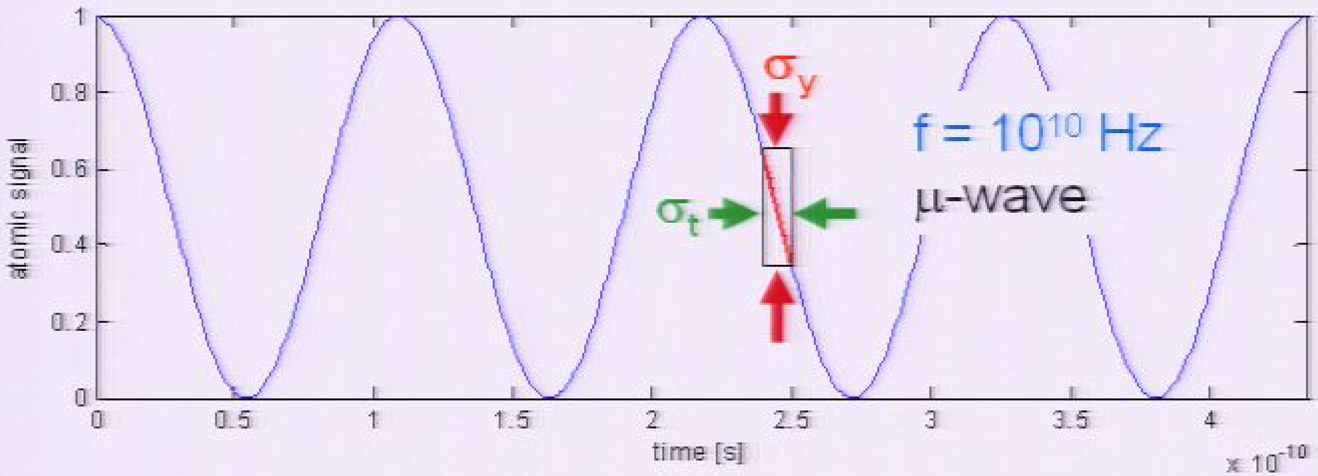

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- For μ-wave (NIST-F1) $\sigma_y = 0.01$

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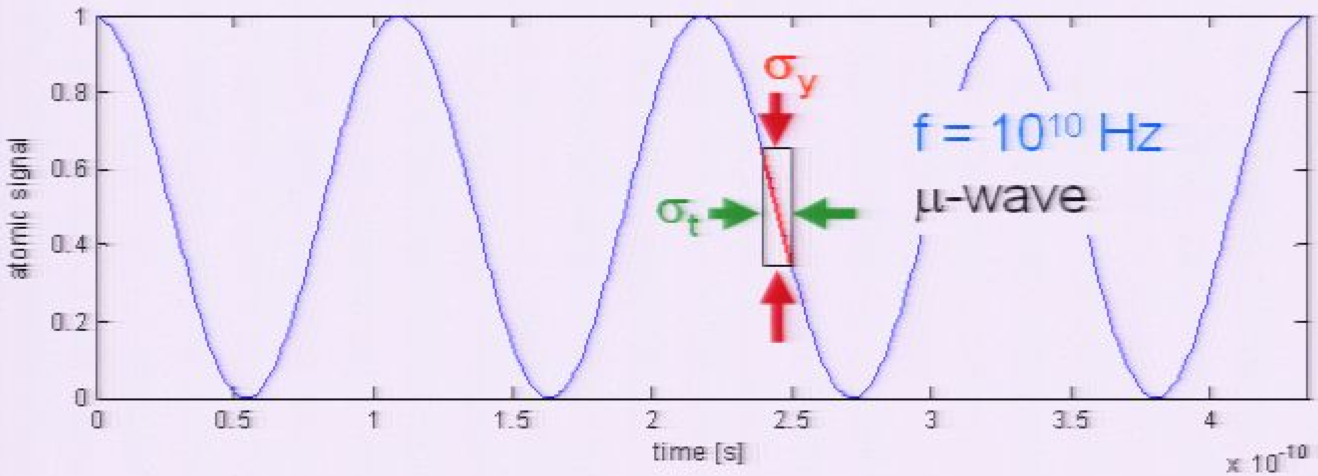

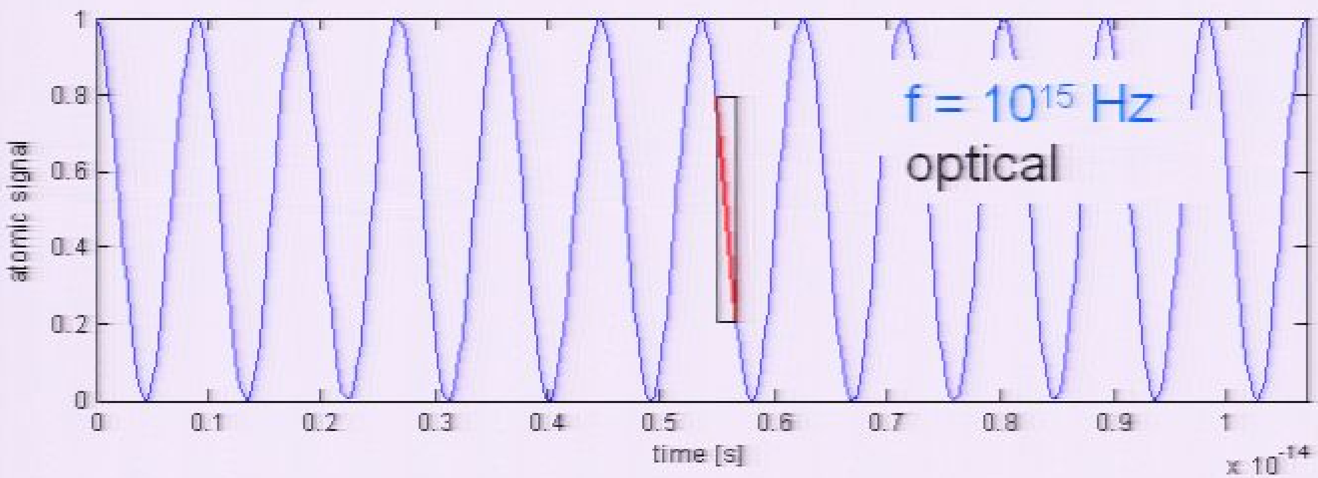

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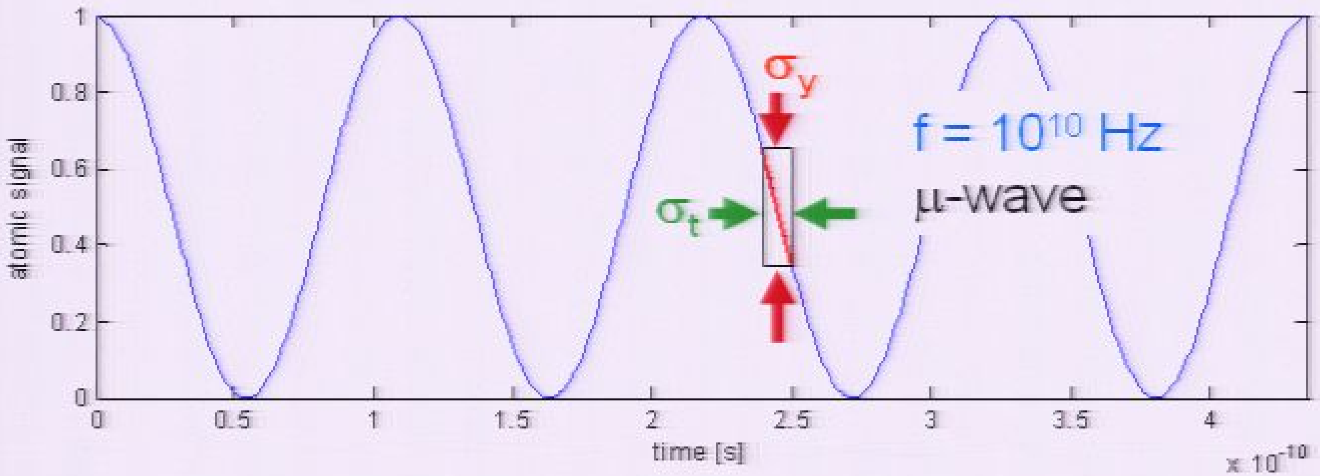

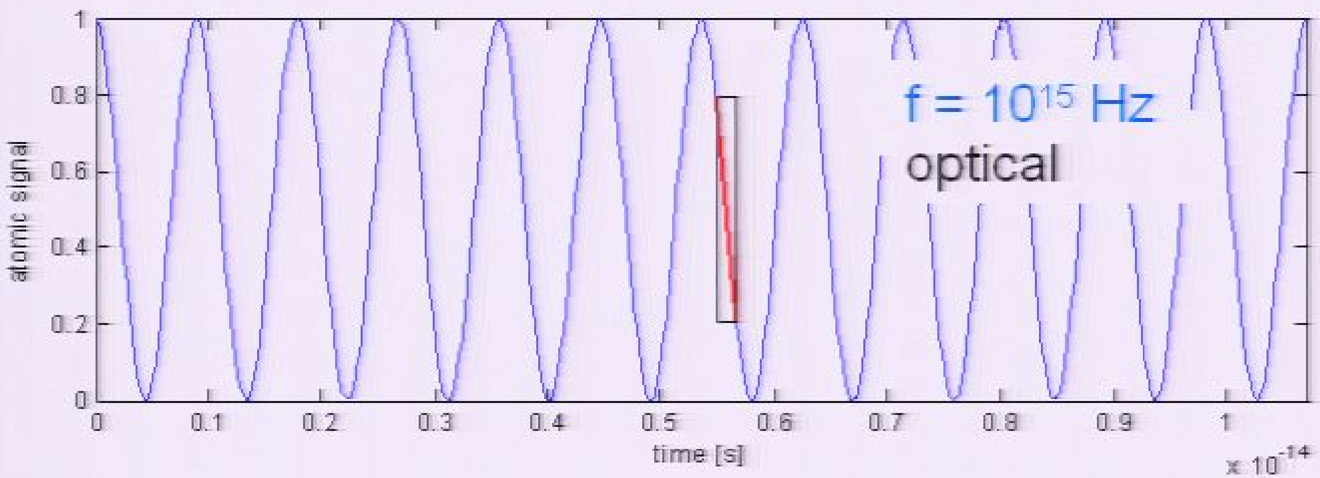

- Atomic reference oscillator
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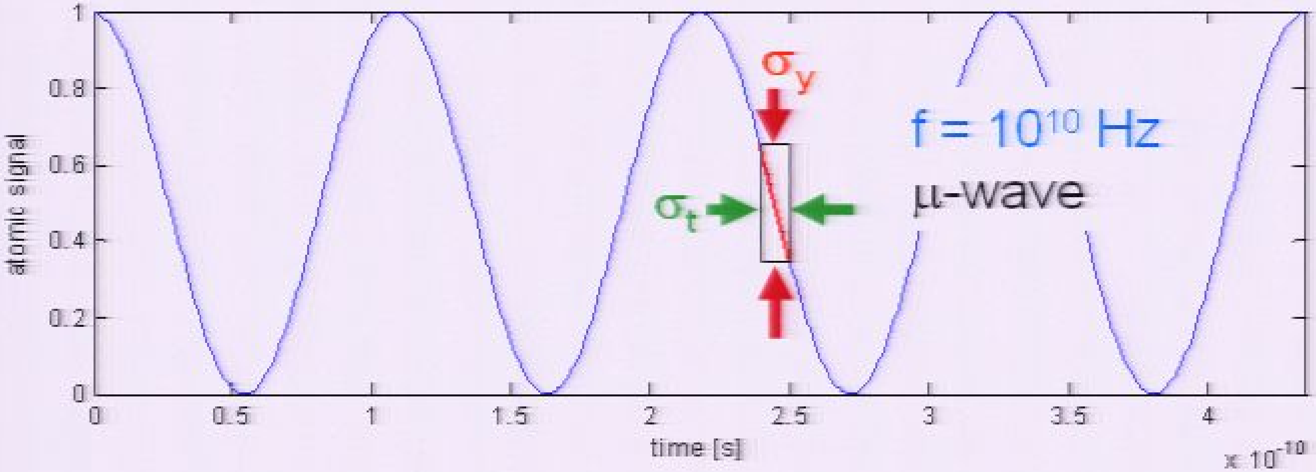
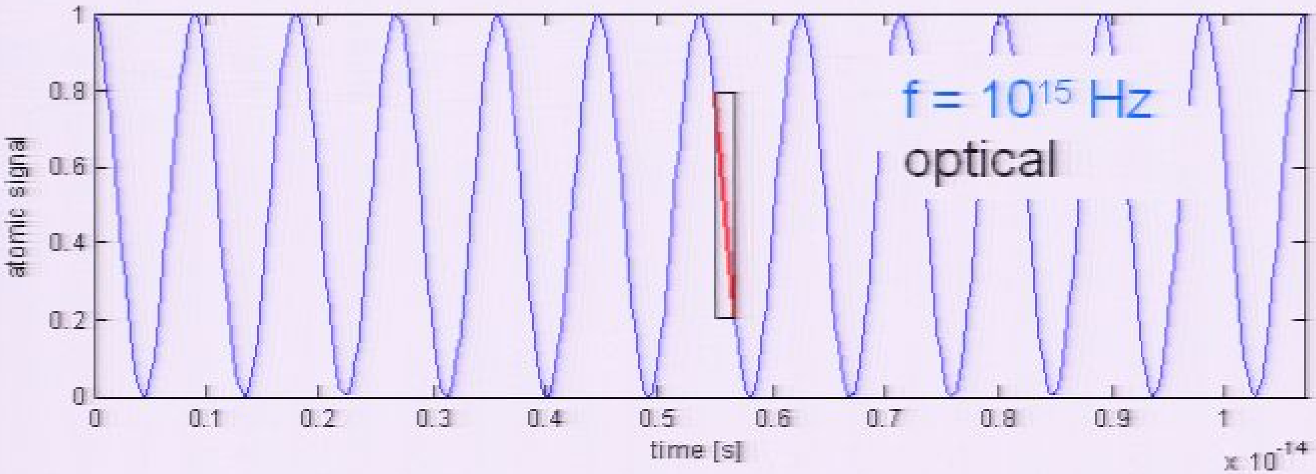
- Time error: $\sigma_t = \sigma_y / (2\pi f)$
- For μ-wave (NIST-F1) $\sigma_y = 0.01$
- For optical single ion clocks $\sigma_y = 0.5$

Stability of microwave and optical atomic clocks (single measurement)





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- For optical clocks, f is 100 000 x larger

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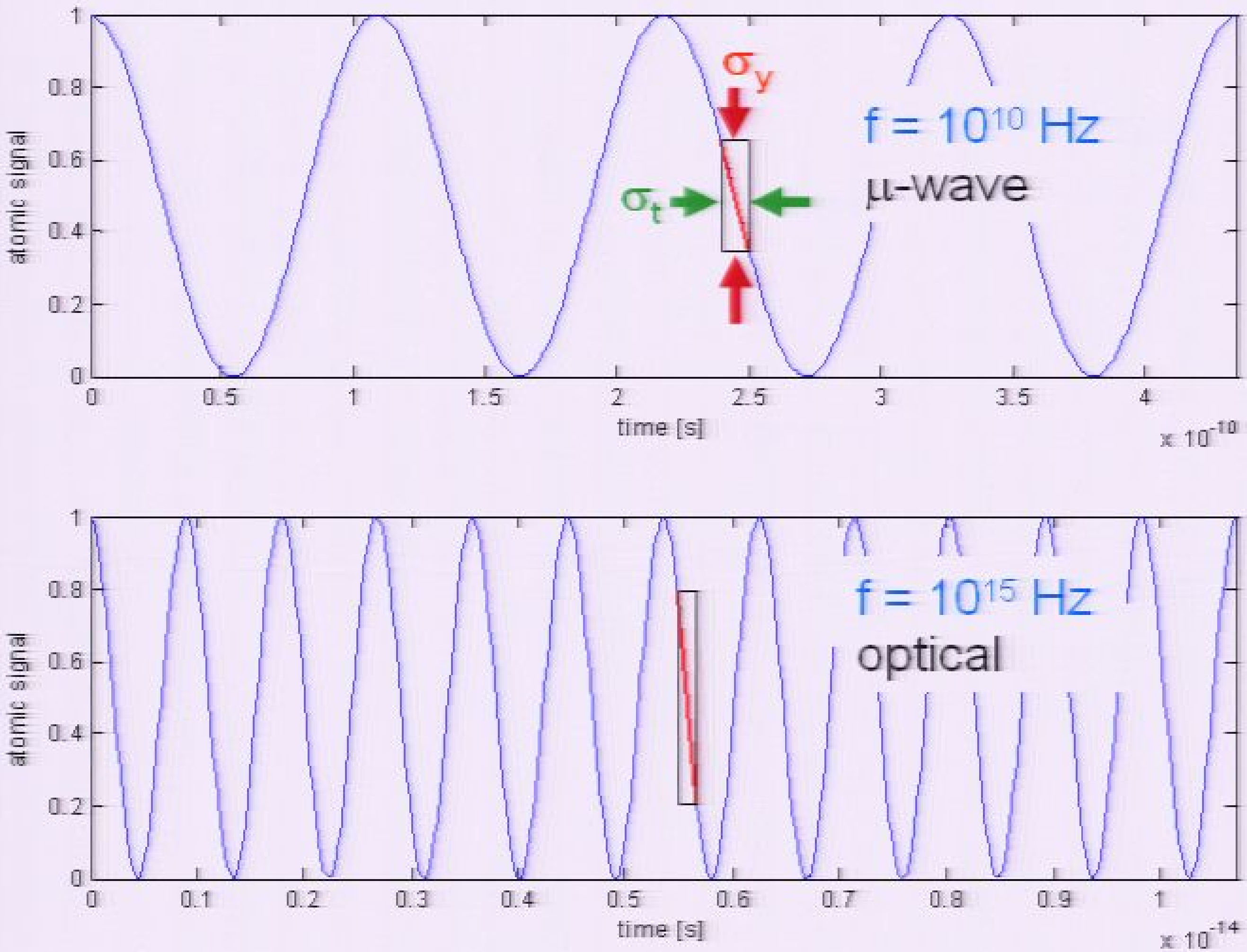

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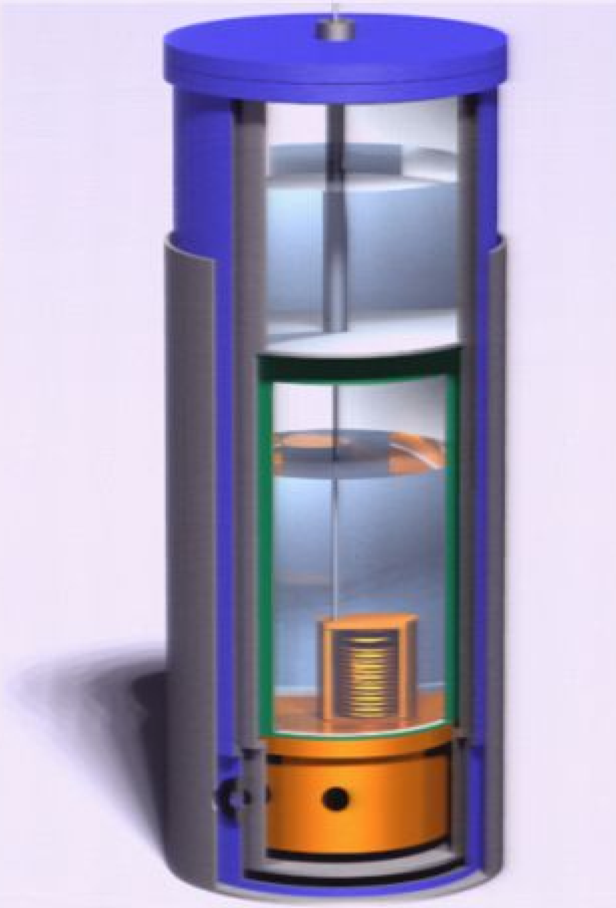
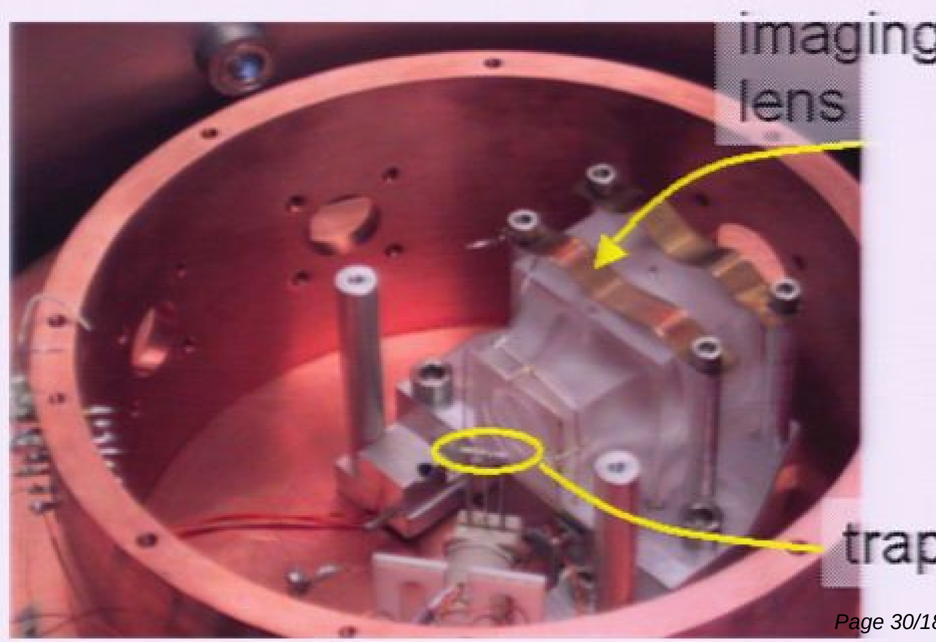
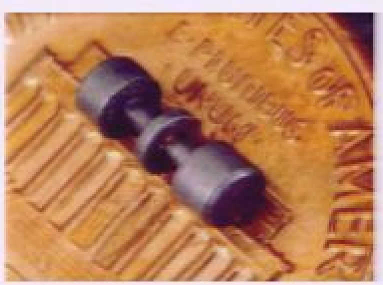
- Measurement error: σ_y
- Time error: $\sigma_t = \sigma_y / (2\pi f)$
- For μ-wave (NIST-F1) $\sigma_y = 0.01$
- For optical single ion clocks $\sigma_y = 0.5$
- For optical clocks, f is 100 000 x larger
- Optical time error σ_t is 100 - 1000 x smaller

$^{199}Hg^{+}$ ion trap



- Trap Details
  - Spherical Paul Trap
  - Cryogenic environment (4 K)





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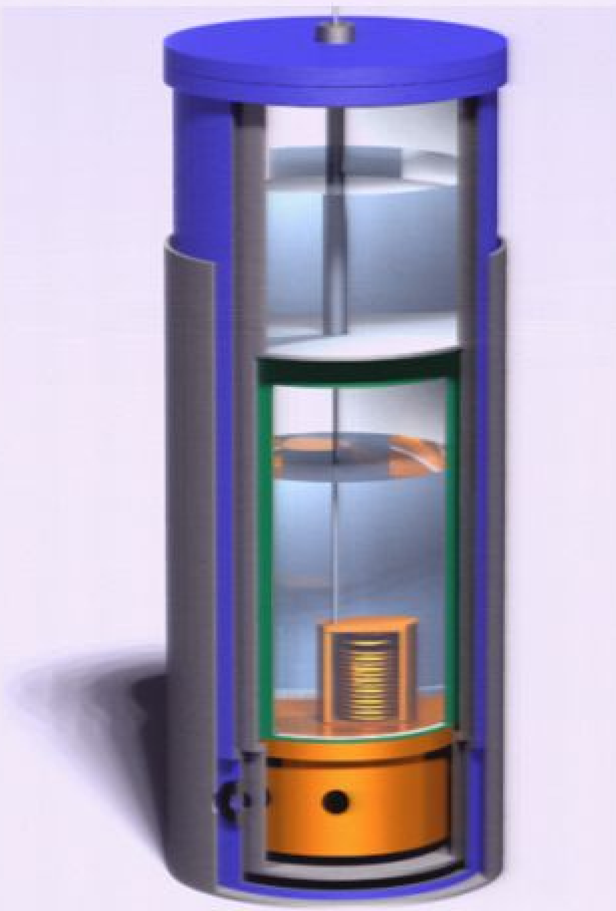

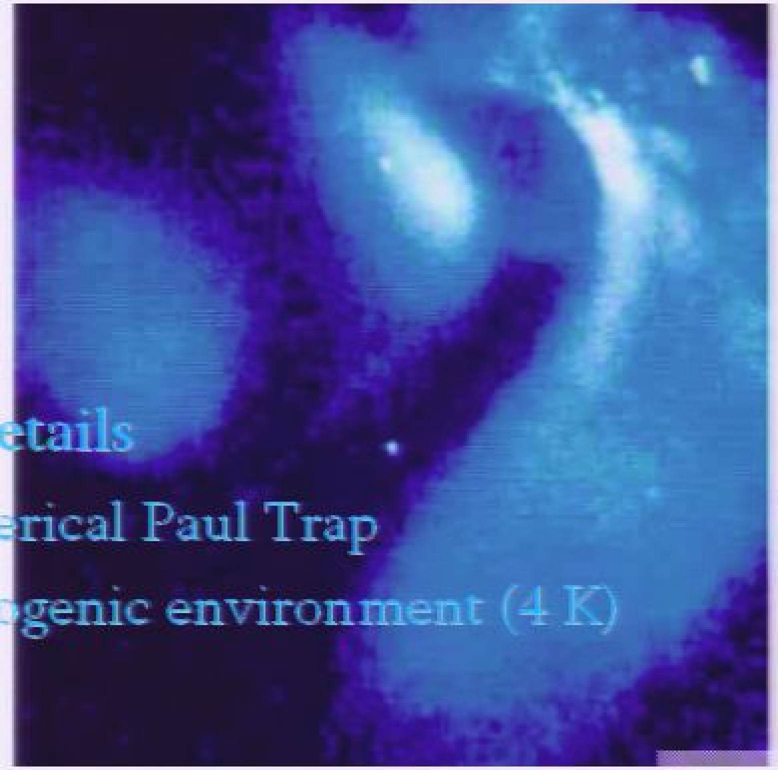

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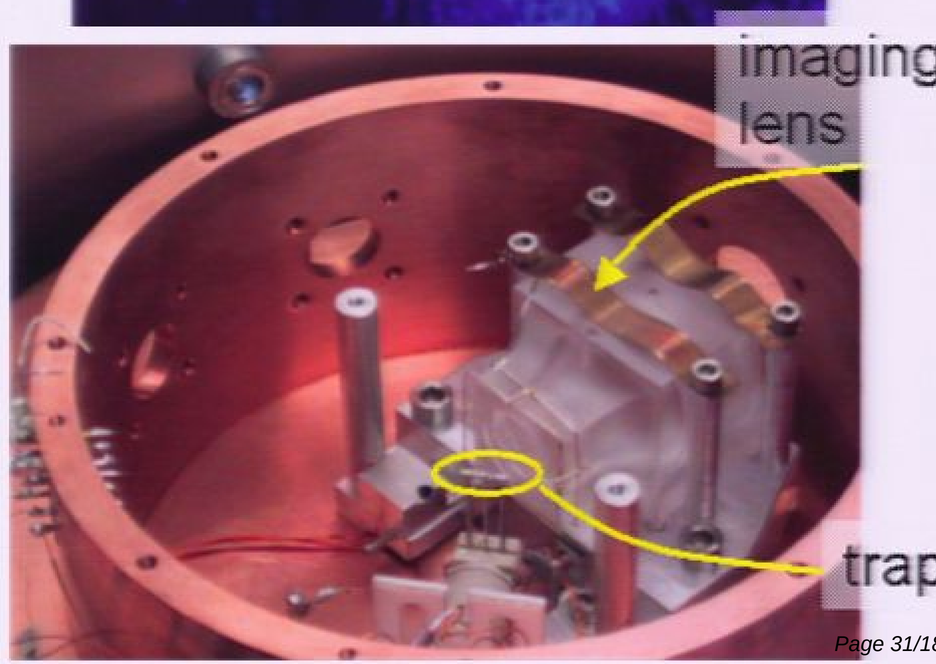
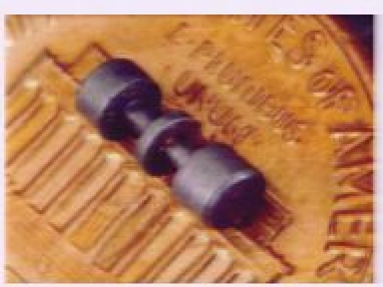


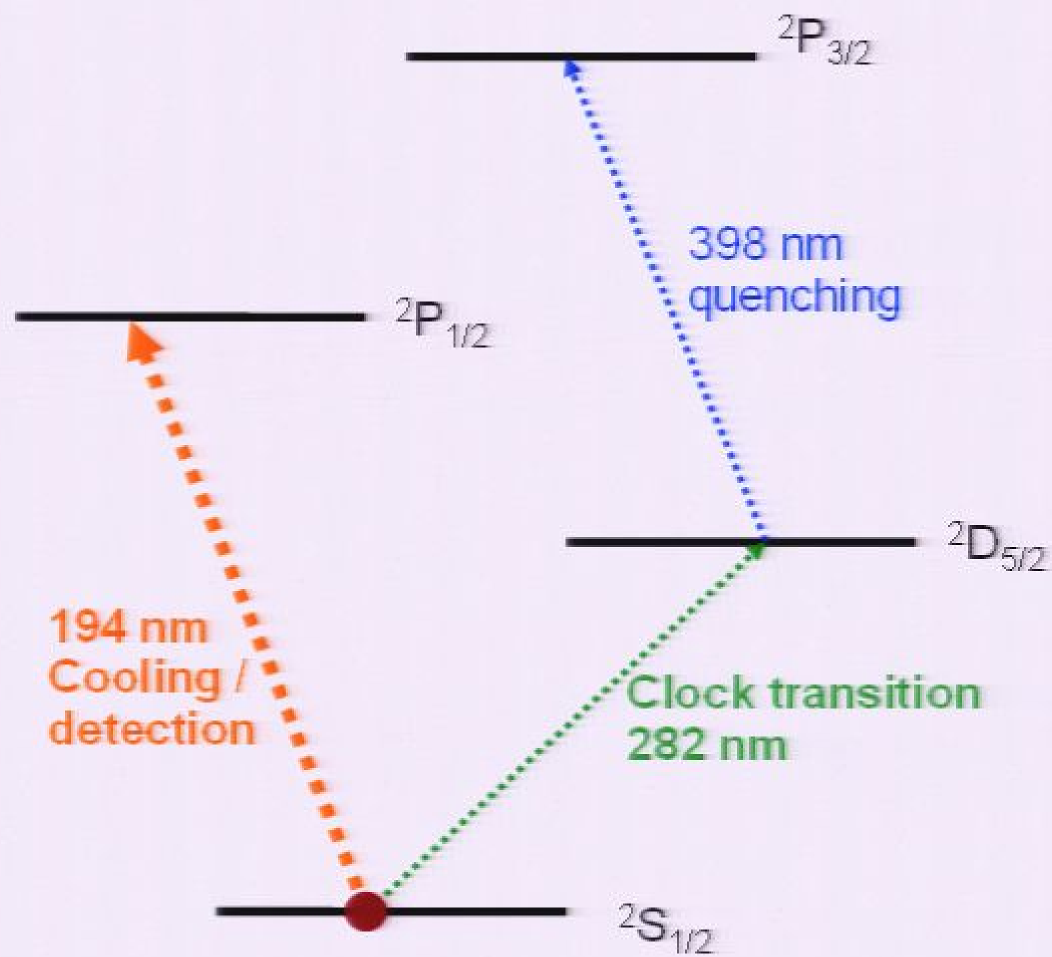


Initial state $^2S_{1/2}$

Quantum Jump Spectroscopy

[How to measure the state of a single atom]

$^{199}Hg^+$



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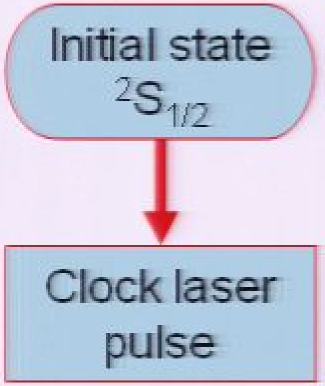

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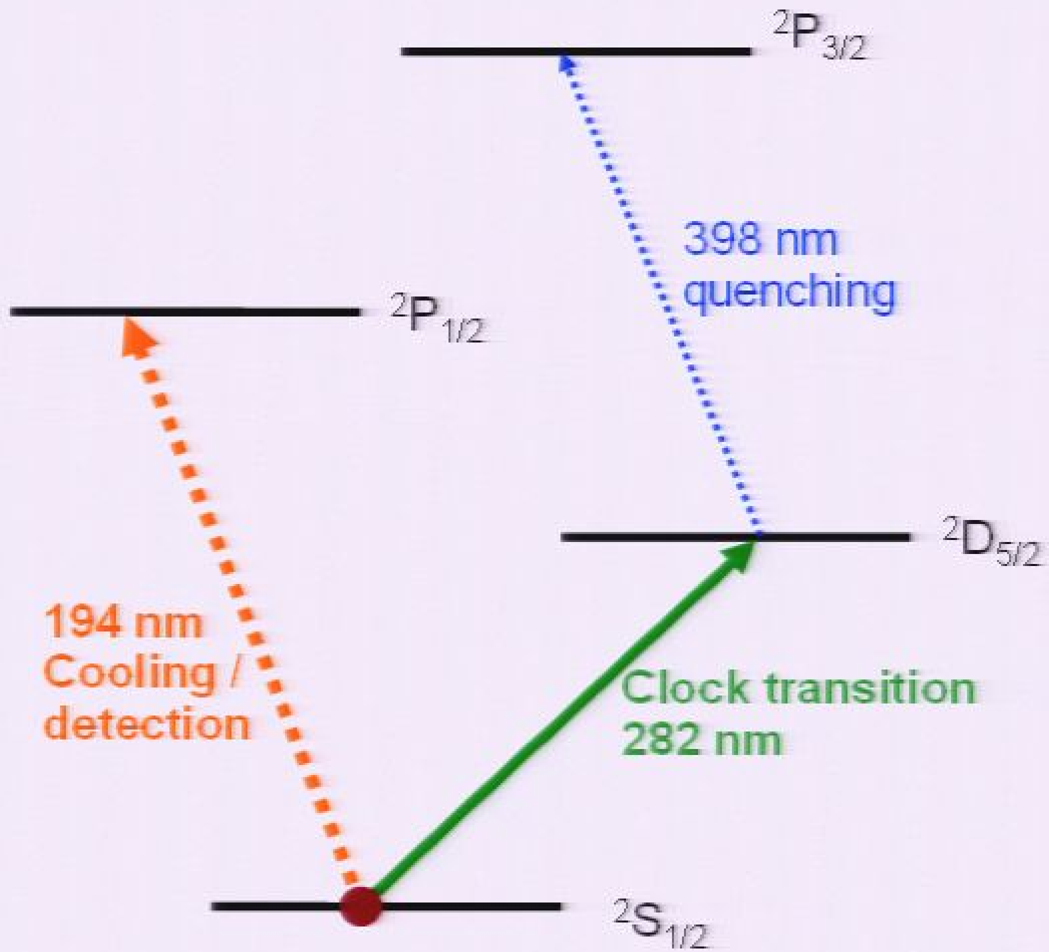

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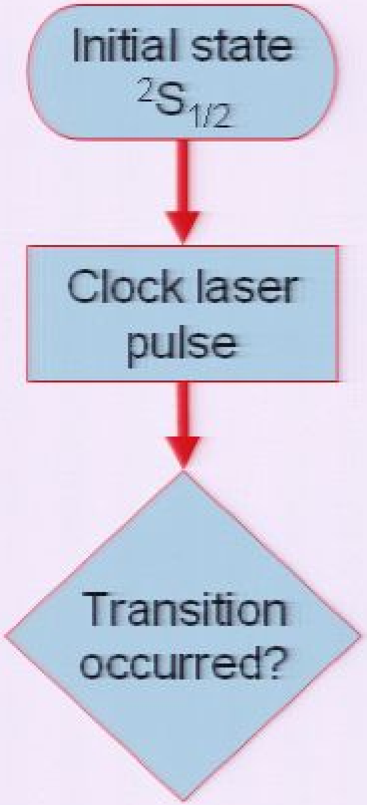

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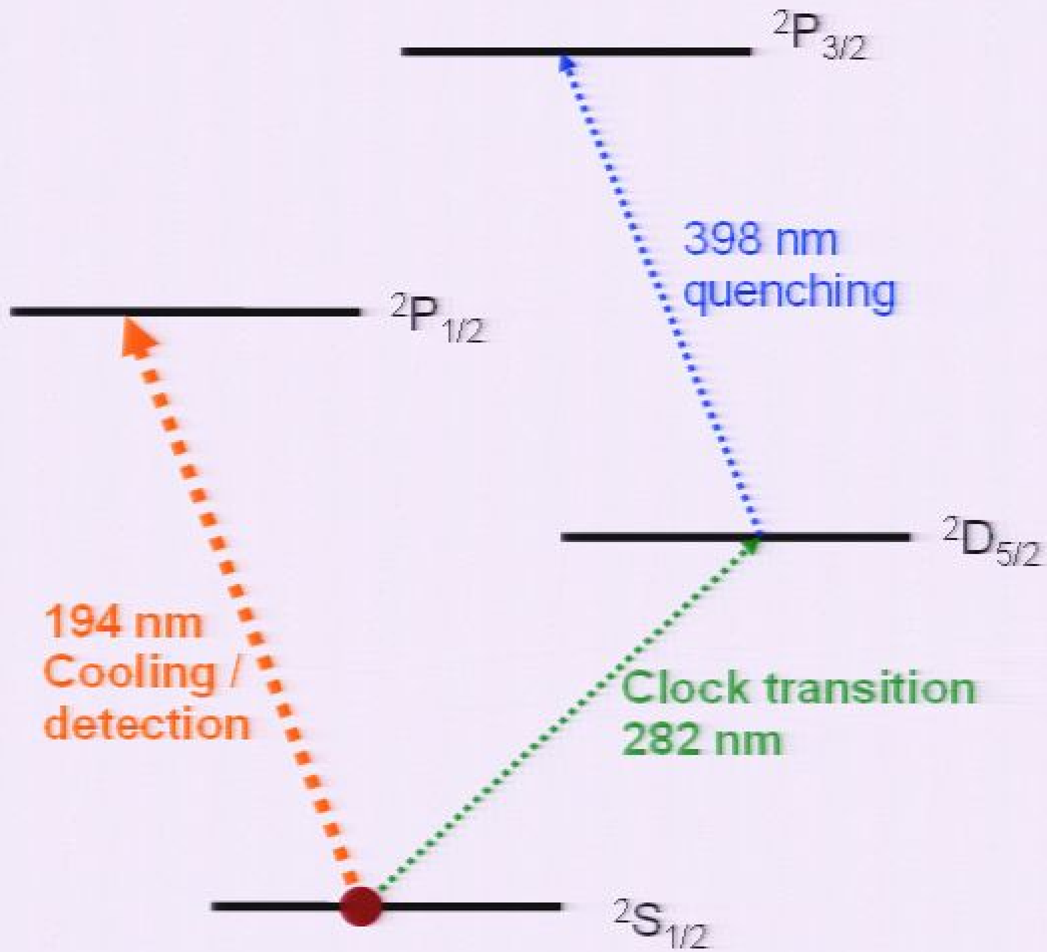

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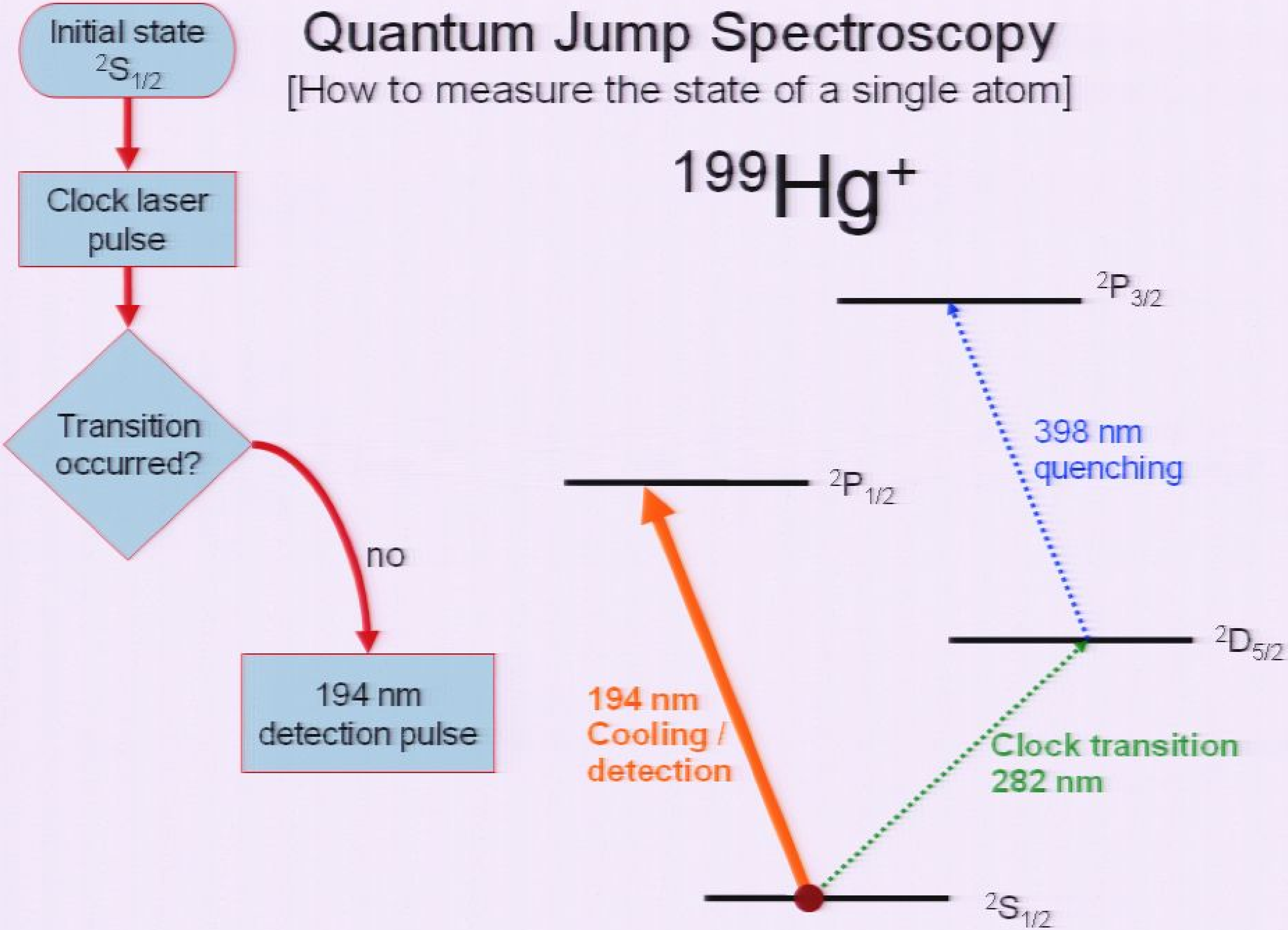

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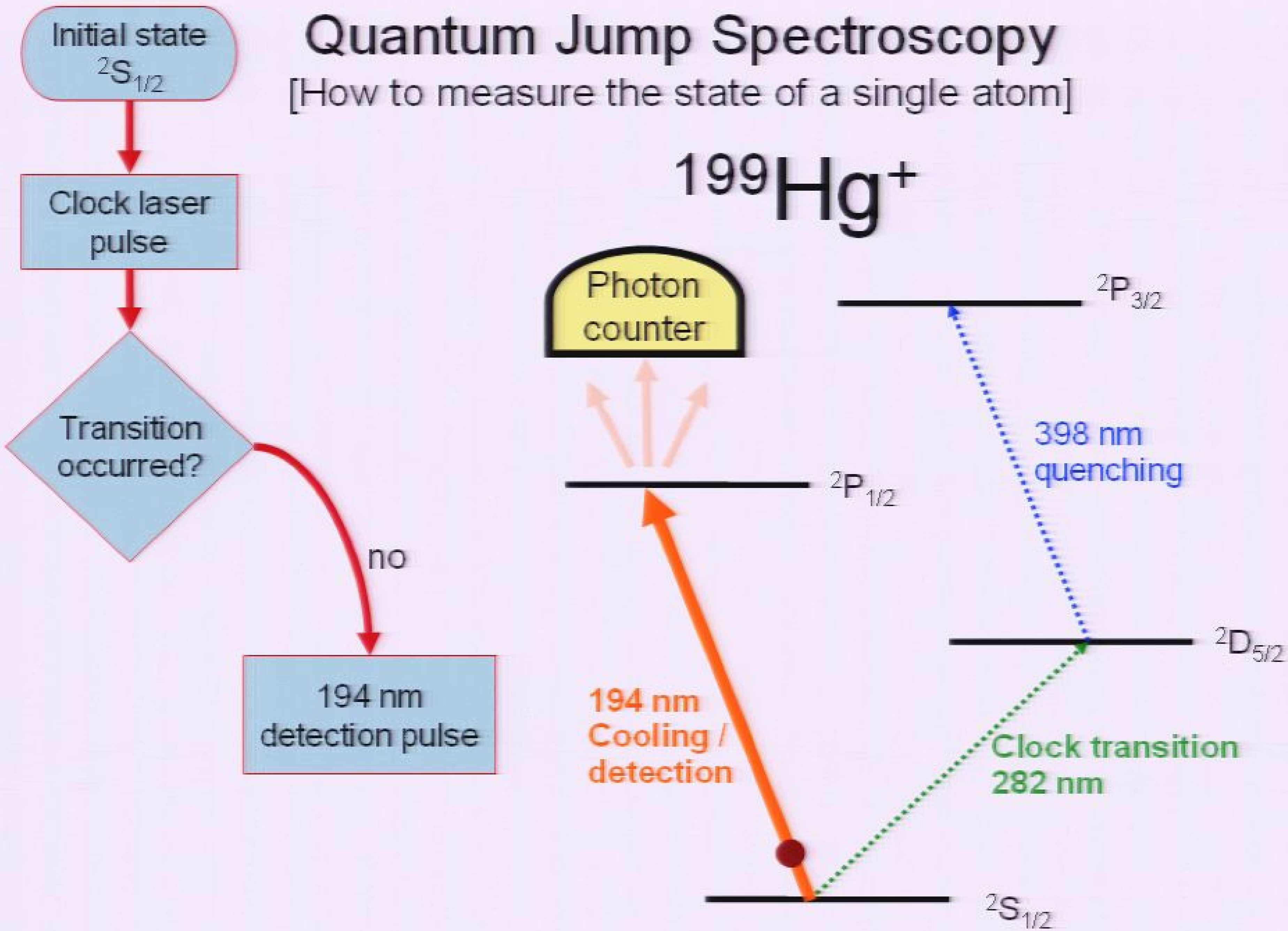

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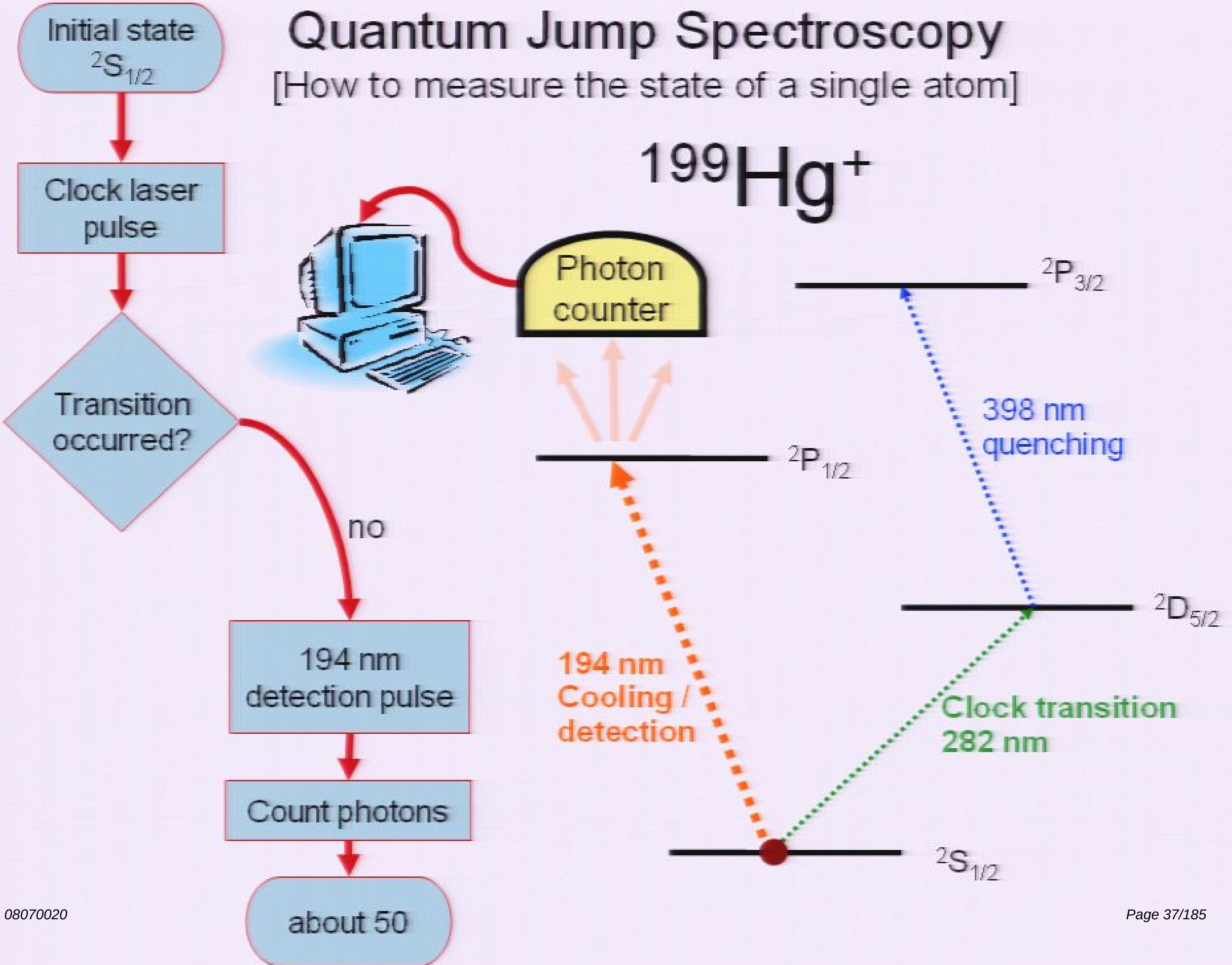

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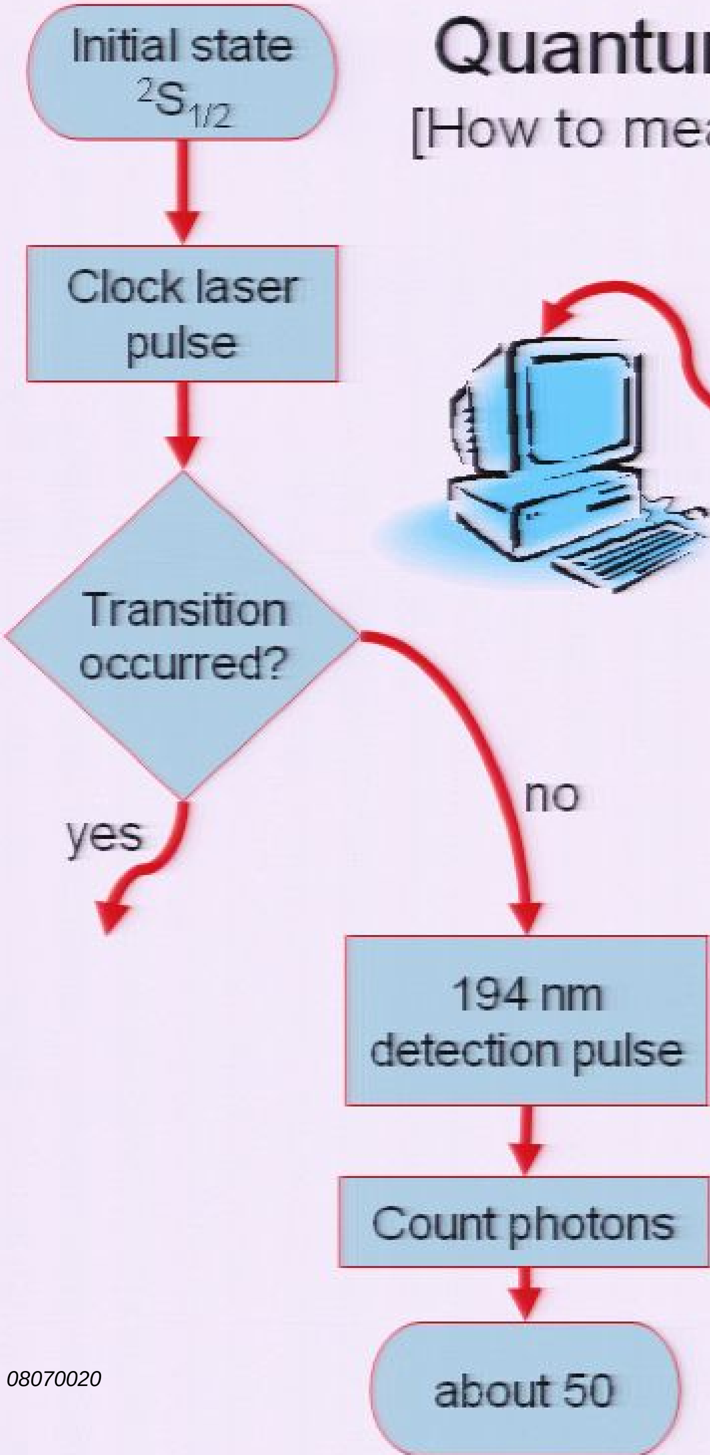
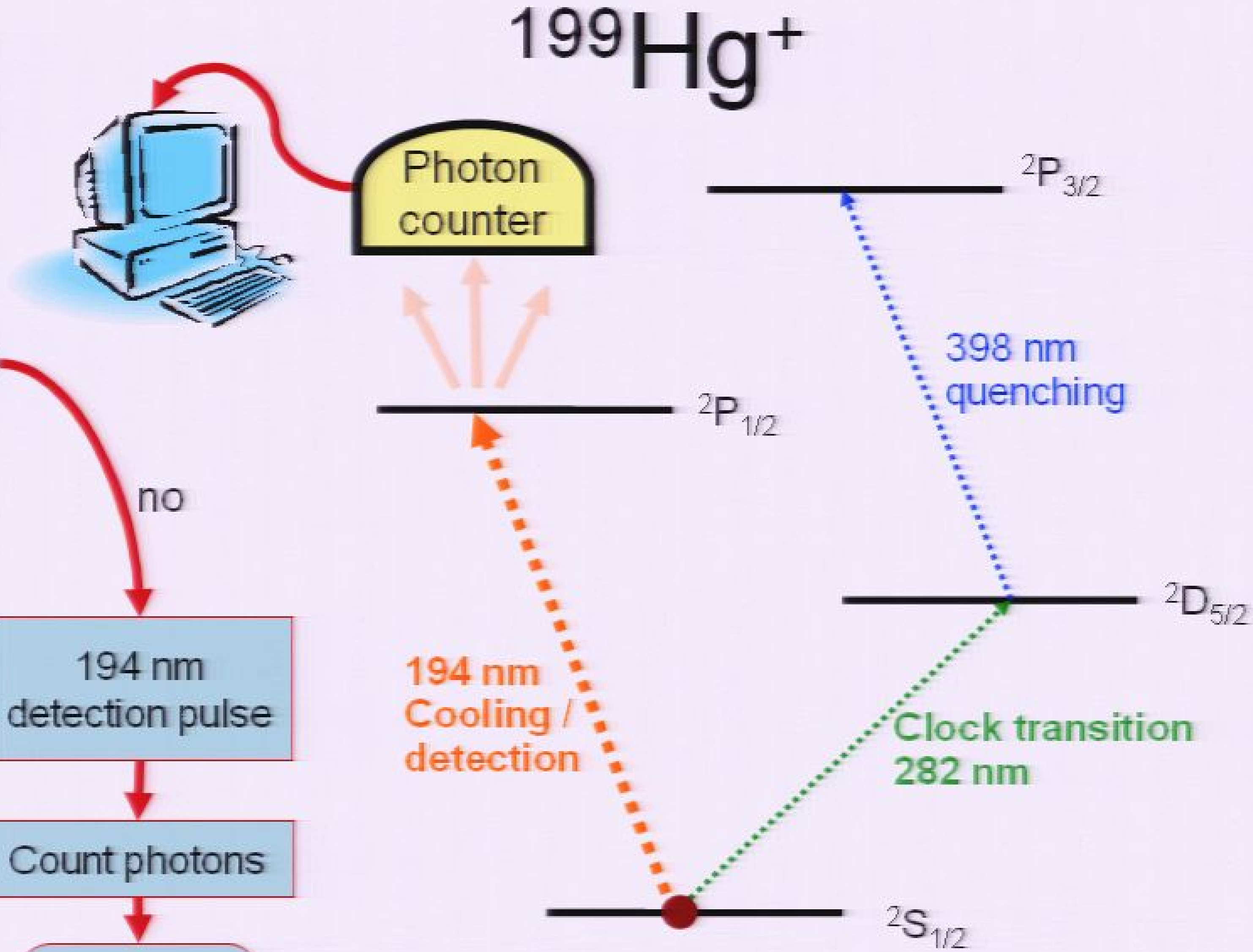
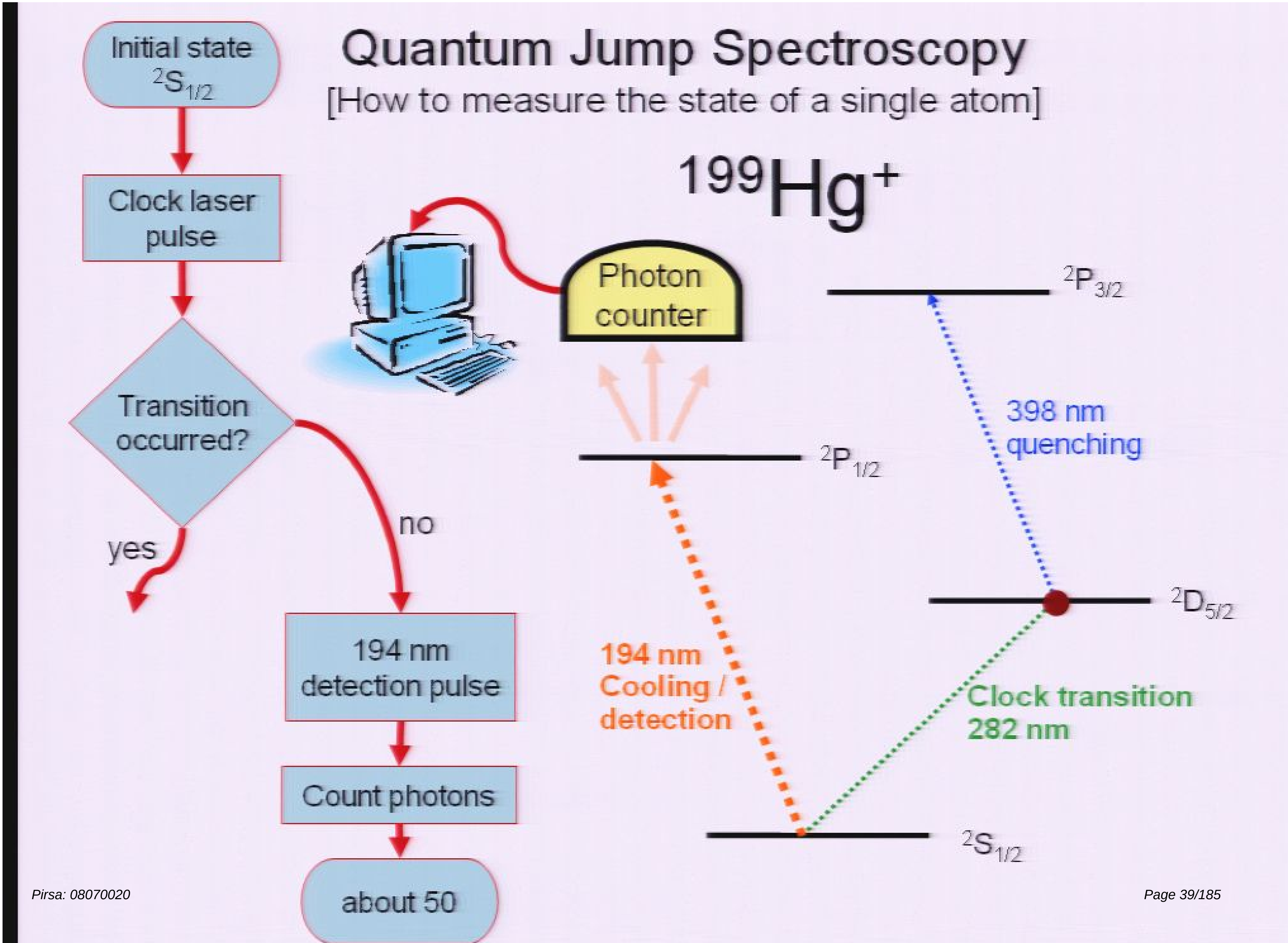
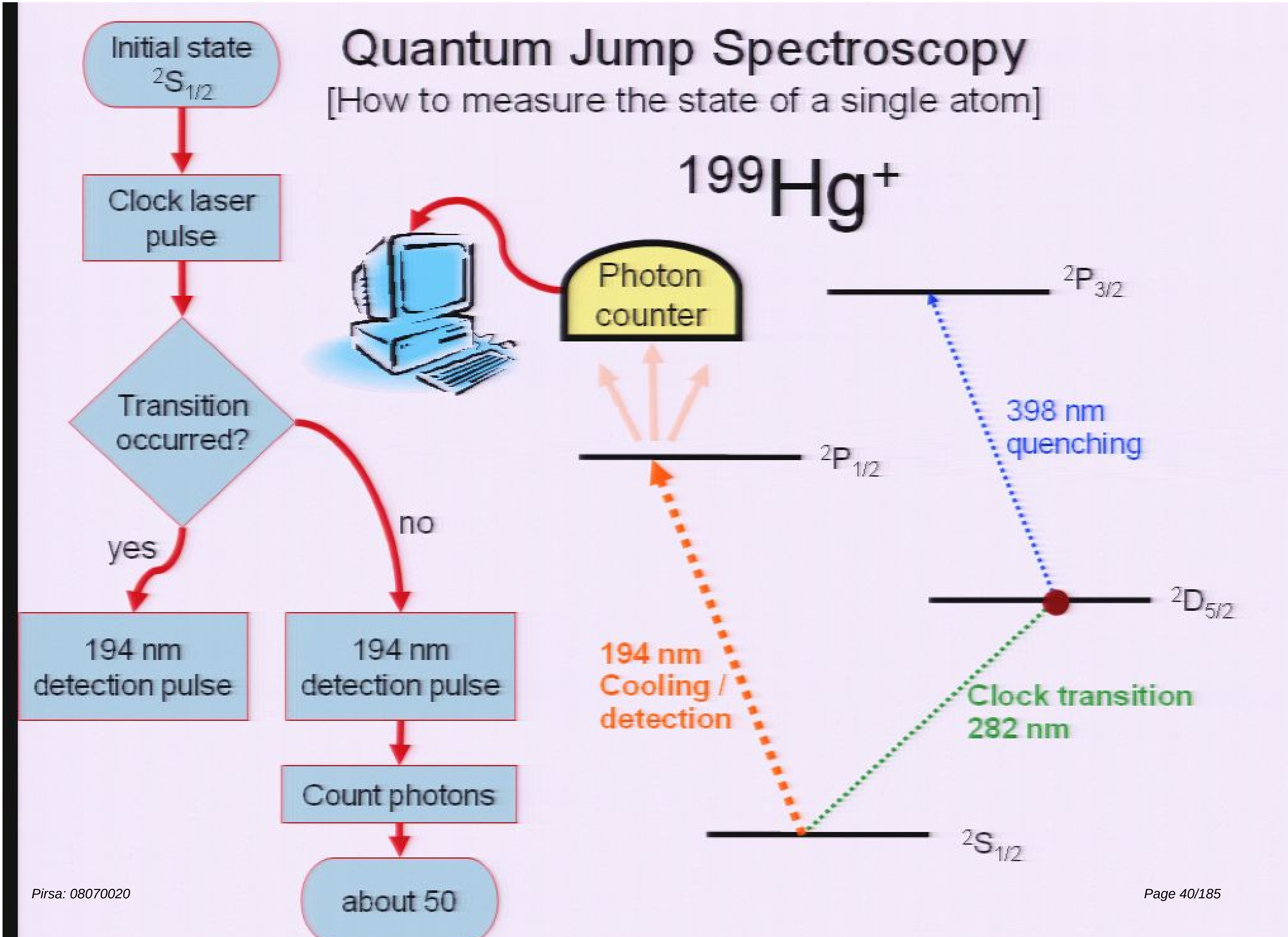






Quantum Jump Spectroscopy
[How to measure the state of a single atom]
199Hg+
Initial state
2S1/2
Clock laser pulse
Transition occurred?
yes
no
194 nm detection pulse
Count photons
about 50
Photon counter
2P3/2
2P1/2
398 nm quenching
2D5/2
194 nm Cooling / detection
Clock transition 282 nm
2S1/2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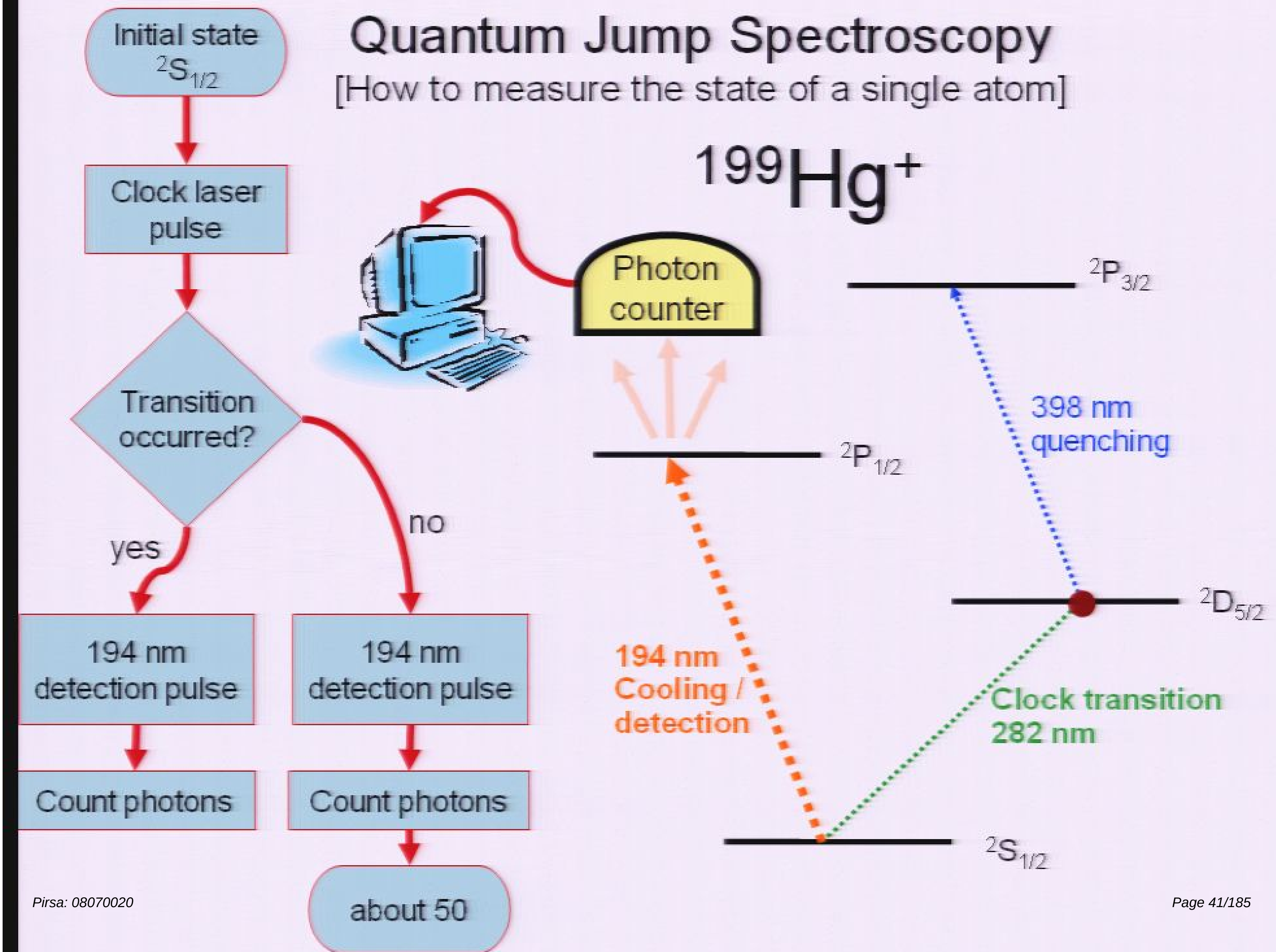

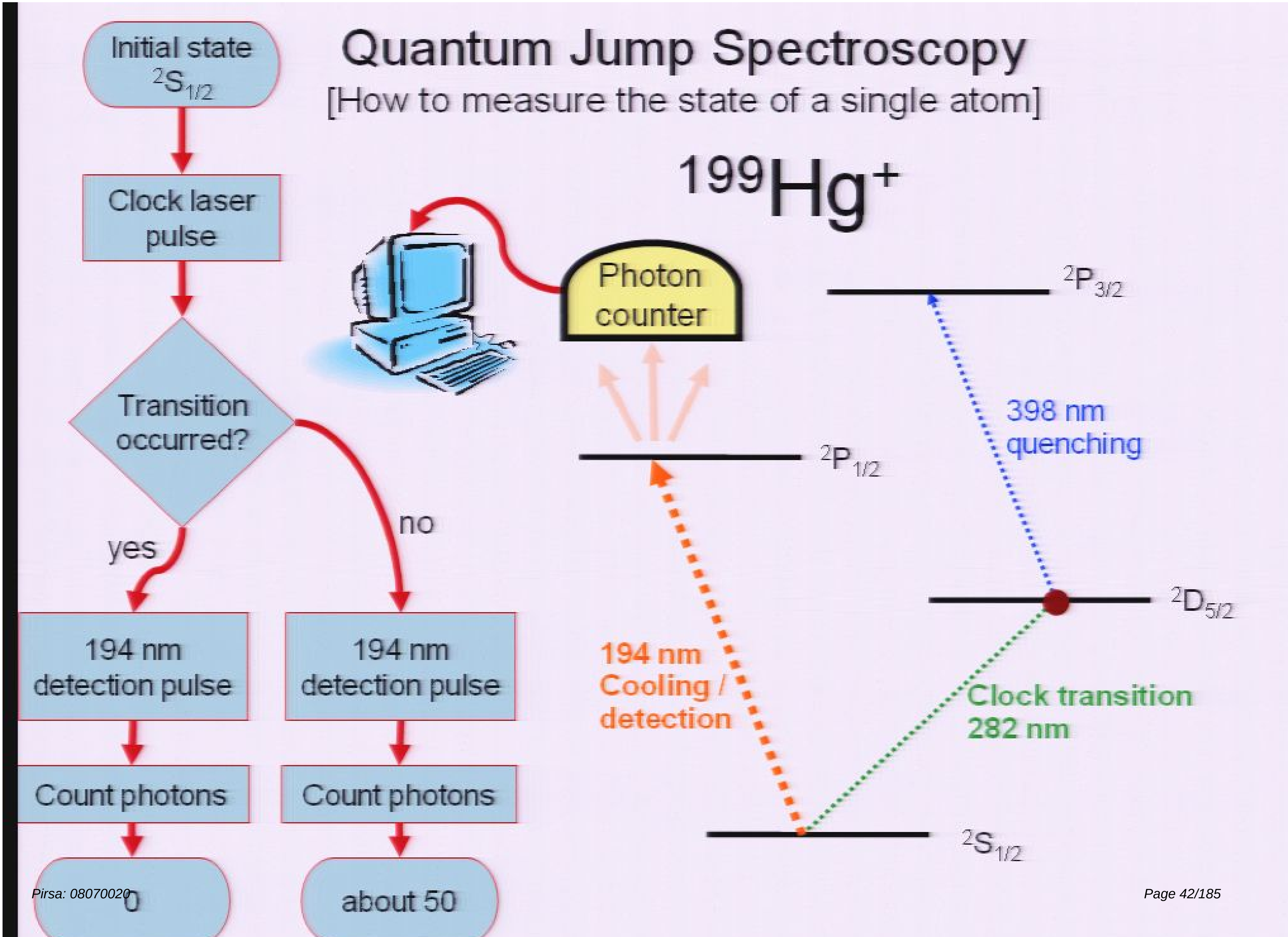
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Initial state $^2S_{1/2}$
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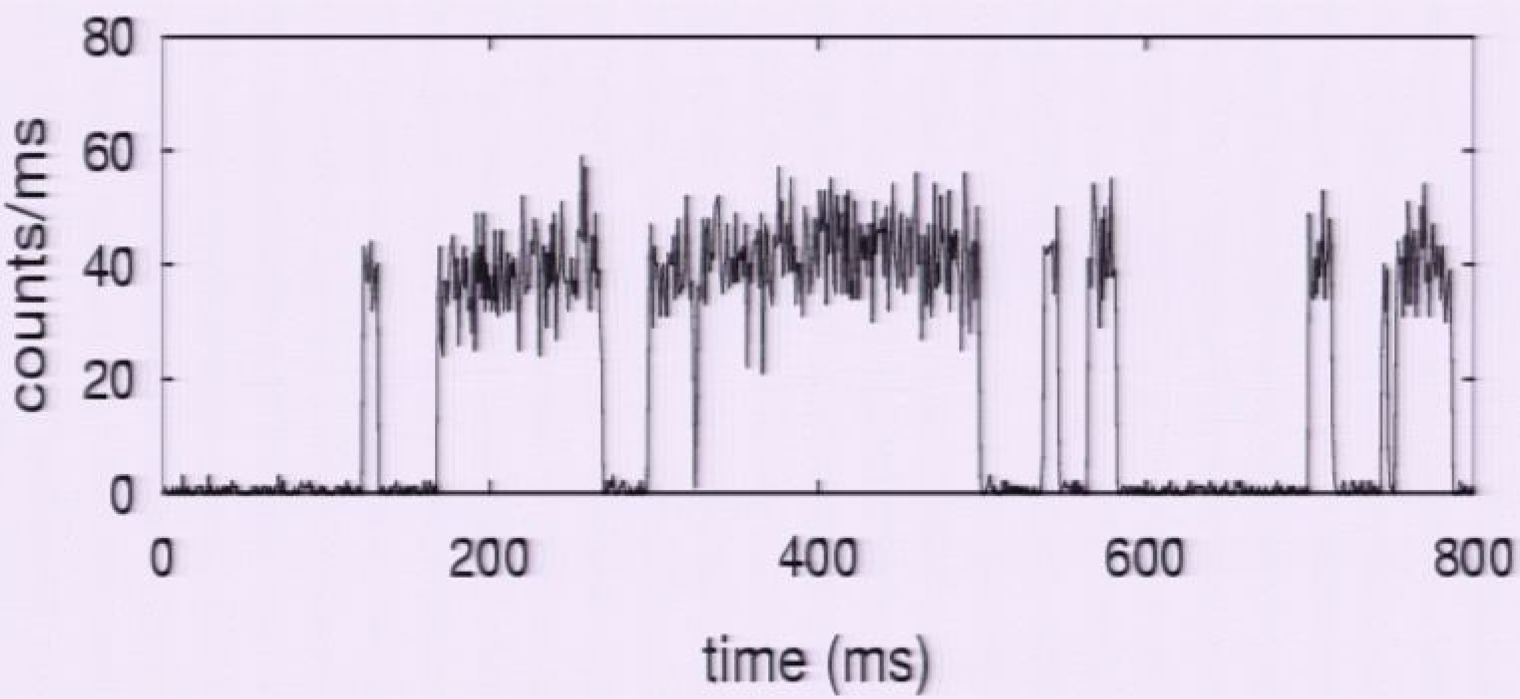
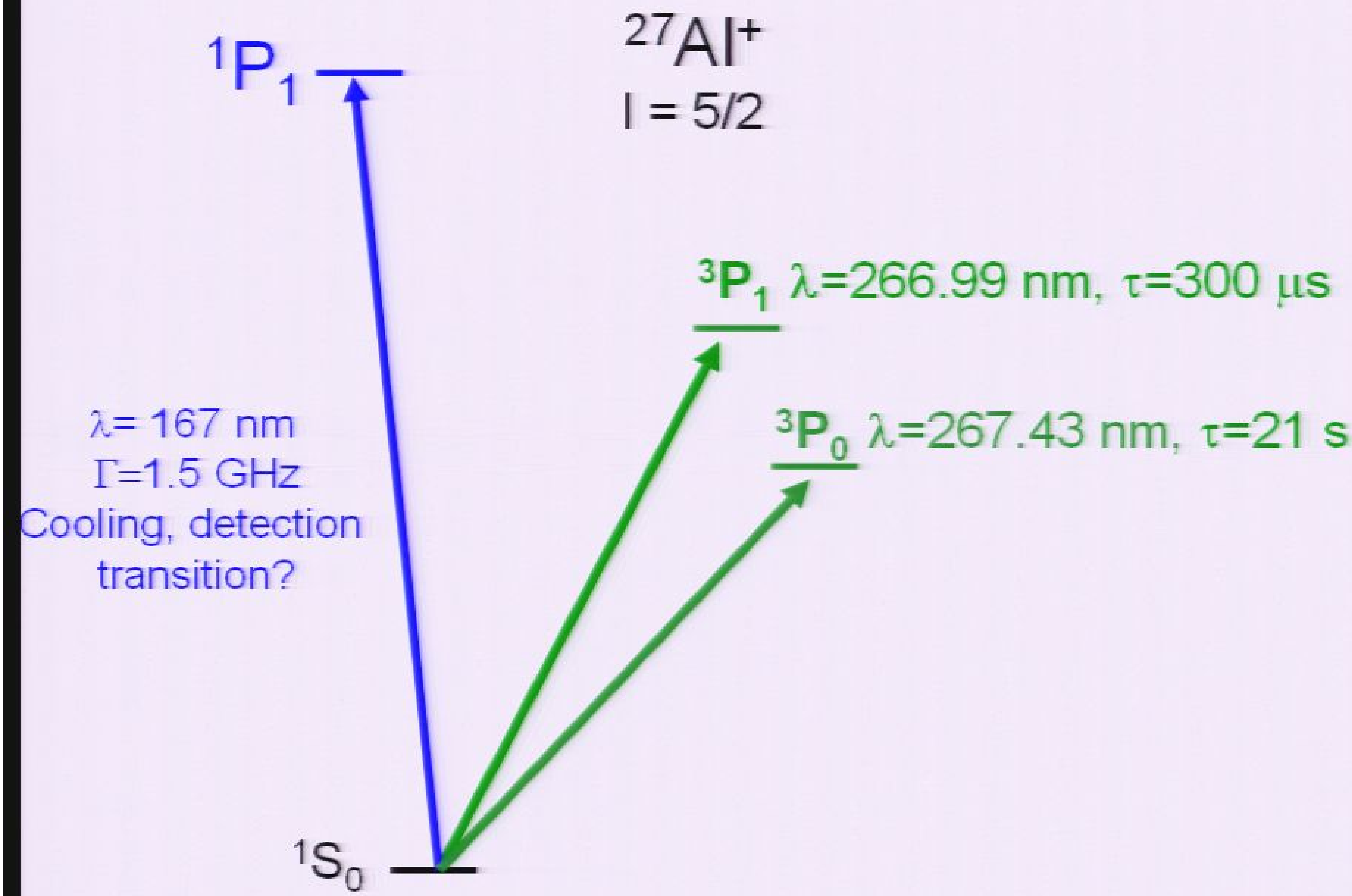
194 nm detection pulse
194 nm detection pulse
Count photons
Count photons
0
about 50
Photon counter
$^2P_{3/2}$
398 nm quenching
$^2P_{1/2}$
$^2D_{5/2}$
194 nm Cooling / detection
Clock transition 282 nm
$^2S_{1/2}$

Observation of Quantum Jumps in a Single Atom

J. C. Bergquist, Randall G. Hulet, Wayne M. Itano, and D. J. Wineland
Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80303
(Received 23 June 1986)

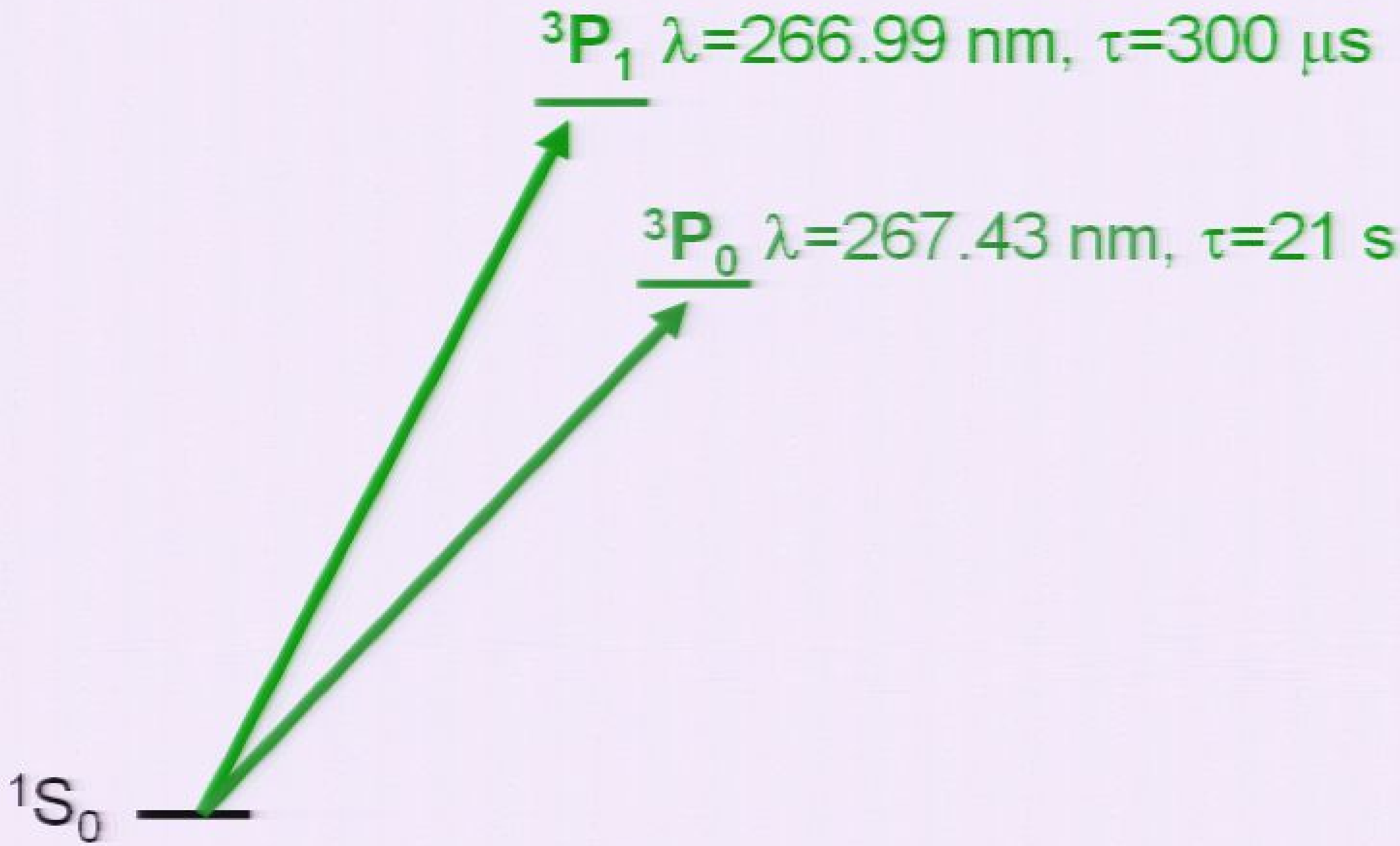




$^{27}Al^{+}$
I = 5/2
$^1P_1$
$^3P_1$ λ=266.99 nm, τ=300 μs
$^3P_0$ λ=267.43 nm, τ=21 s
λ= 167 nm
Γ=1.5 GHz
Cooling, detection
transition?
$^1S_0$

$^{27}Al^+$

$I = 5/2$



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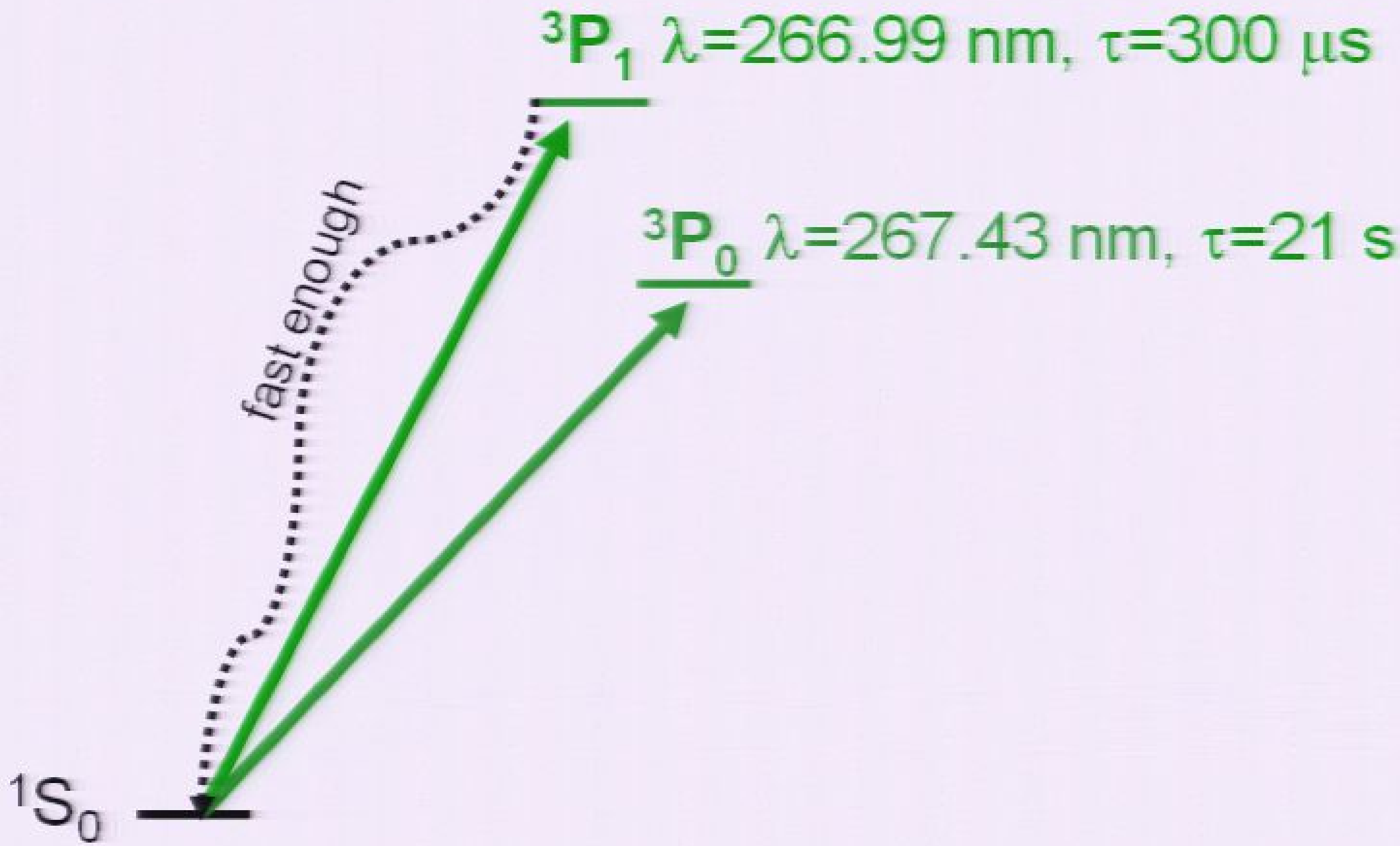
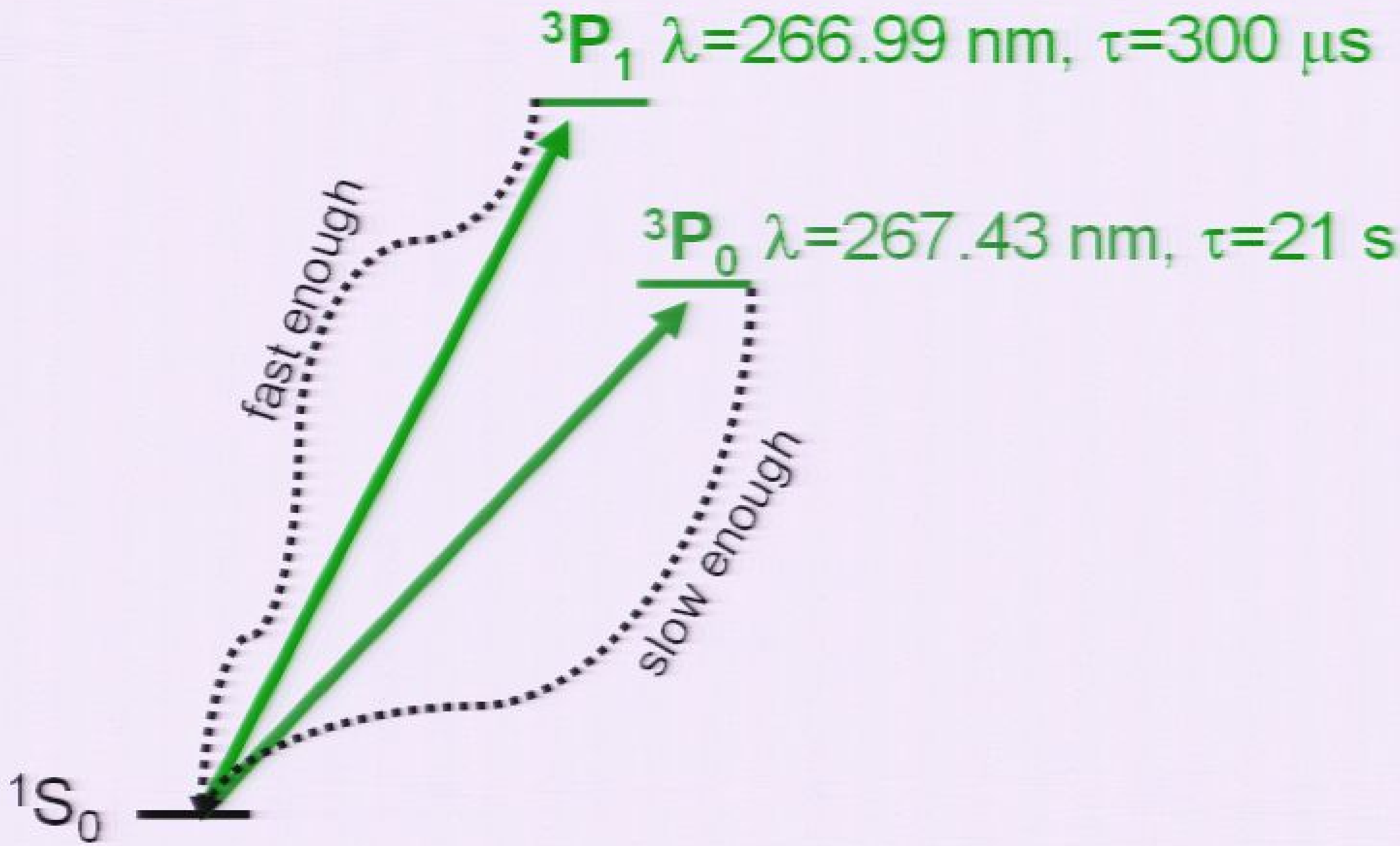


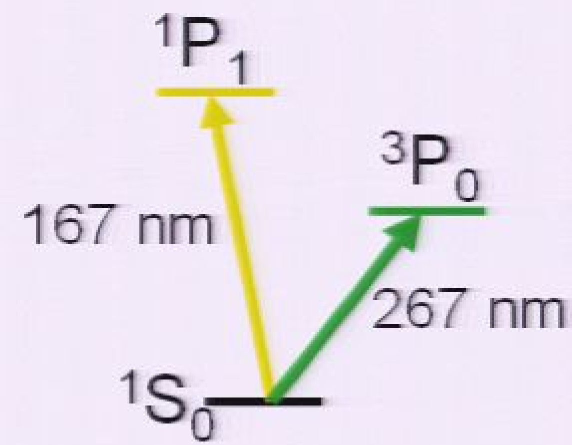
$^{27}Al^{+}$

$I = 5/2$



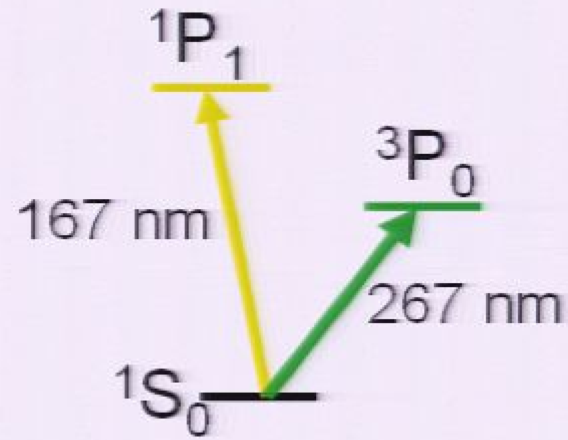
$^3P_1$ λ=266.99 nm, τ=300 μs
$^3P_0$ λ=267.43 nm, τ=21 s
fast enough
slow enough
$^1S_0$

Spectroscopy of $^{27}Al^+$



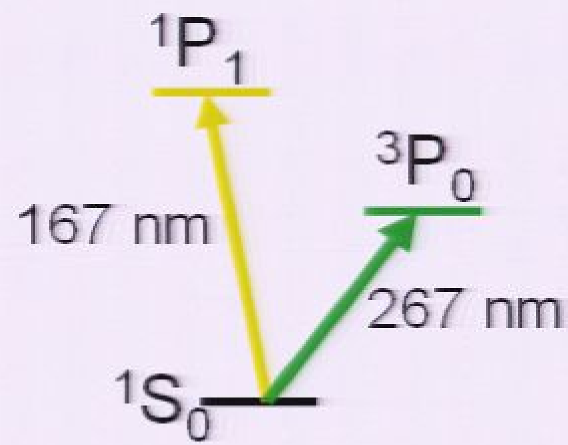
Spectroscopy of $^{27}Al^{+}$

- 8 mHz linewidth clock transition



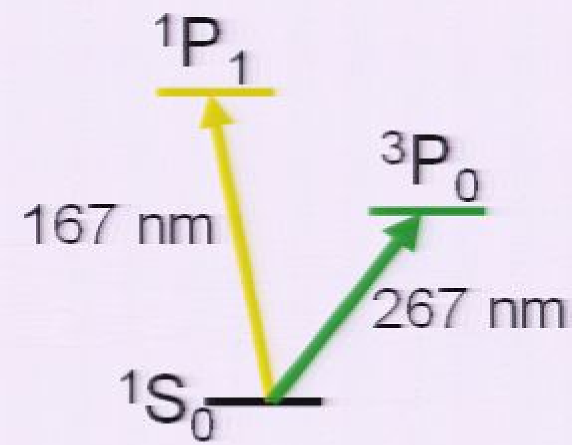
Spectroscopy of $^{27}Al^{+}$

- 8 mHz linewidth clock transition
- Insensitive to external fields



Spectroscopy of $^{27}Al^{+}$

- 8 mHz linewidth clock transition
- Insensitive to external fields
- Smallest known room temperature blackbody shift



Spectroscopy of $^{27}Al^+$

- 8 mHz linewidth clock transition
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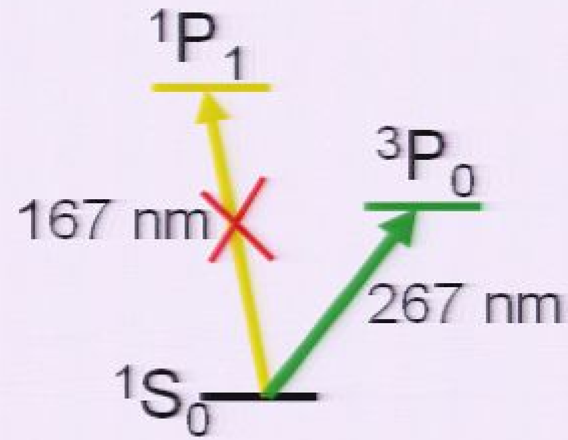
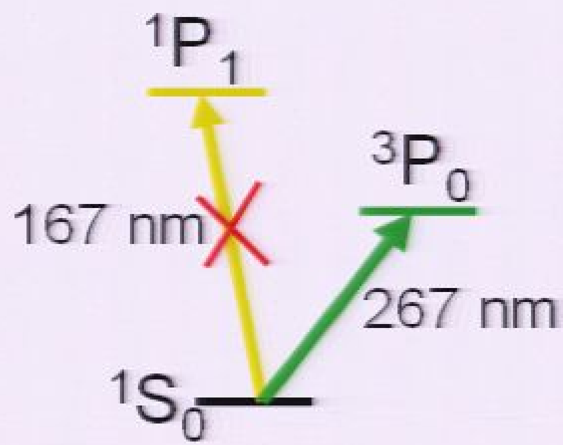
- Smallest known room temperature blackbody shift
- No accessible strong transition for cooling & state detection



Spectroscopy of $^{27}Al^+$

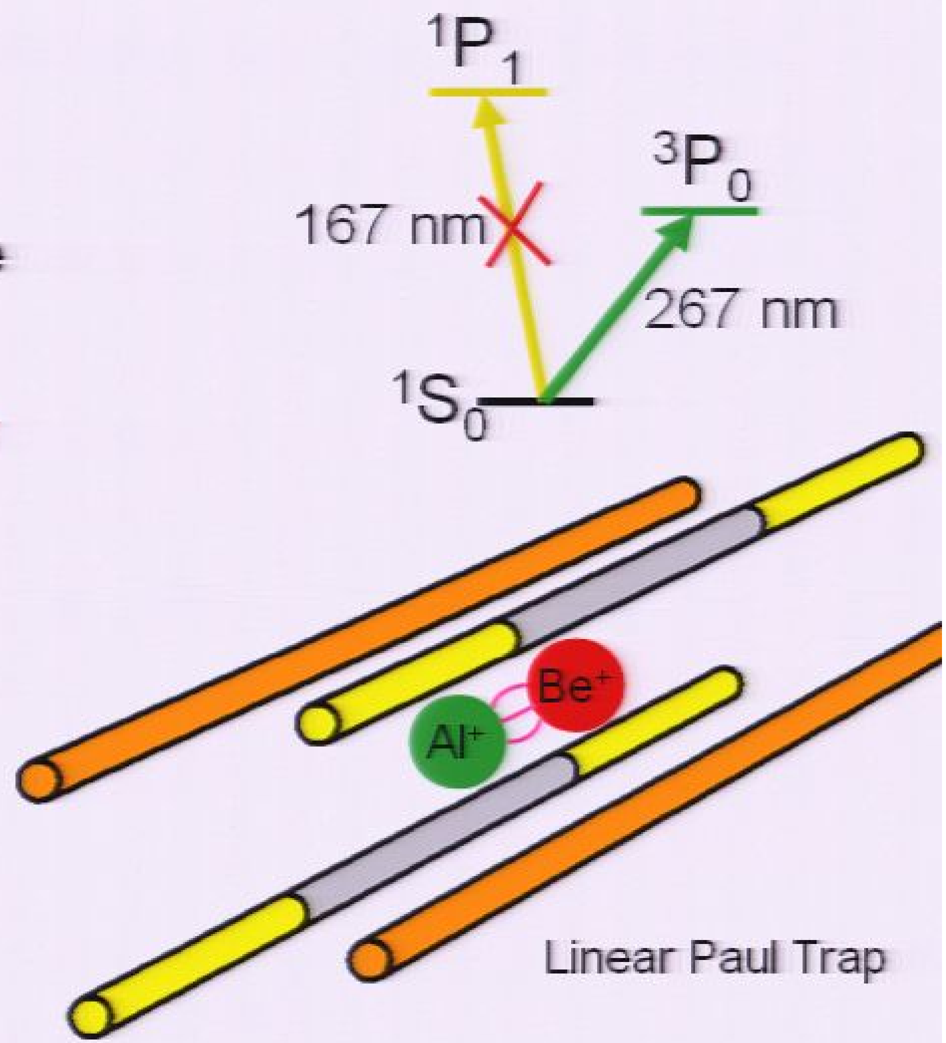
- 8 mHz linewidth clock transition
- Insensitive to external fields
- Smallest known room temperature blackbody shift
- No accessible strong transition for cooling & state detection
- Use two-ion quantum logic techniques with $^9Be^+$ and $^{27}Al^+$ for cooling, state preparation & readout [1]



[1] D.J. Wineland *et al.*, Proc. 6th Symposium on Frequency Standards and Metrology, 2001, pp. 361-368

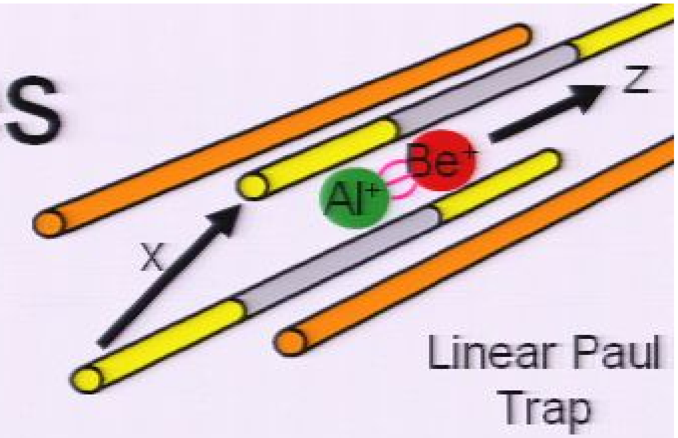
Spectroscopy of $^{27}Al^+$

- 8 mHz linewidth clock transition
- Insensitive to external fields
- Smallest known room temperature blackbody shift
- No accessible strong transition for cooling & state detection
- Use two-ion quantum logic techniques with $^{9}Be^+$ and $^{27}Al^+$ for cooling, state preparation & readout [1]



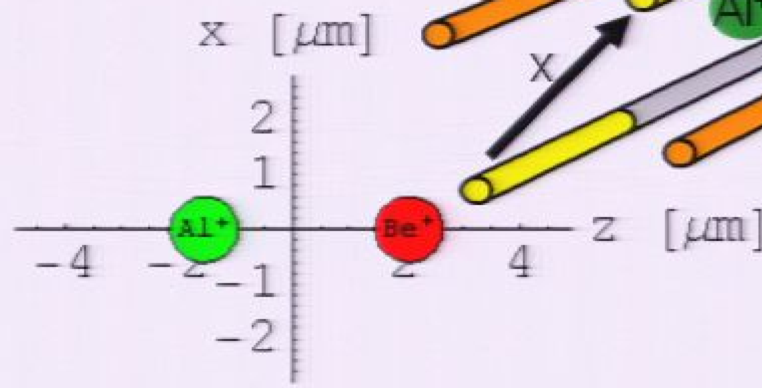
[1] D.J. Wineland *et al.*, Proc. 6th Symposium on Frequency Standards and Metrology, 2001, pp. 361-368

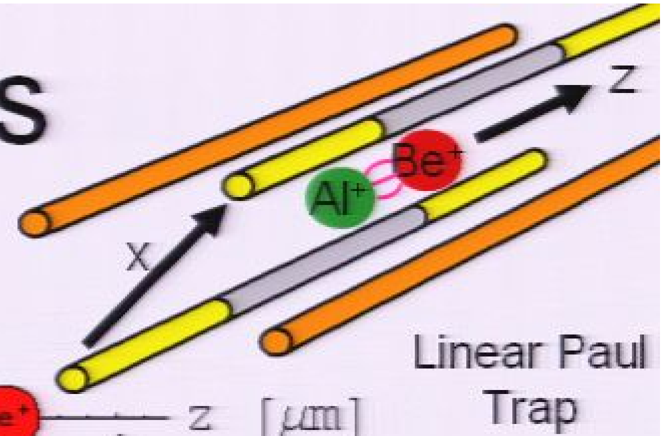
Normal modes



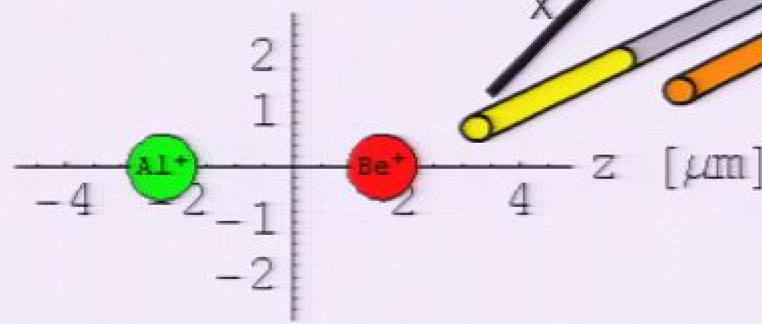
Normal modes

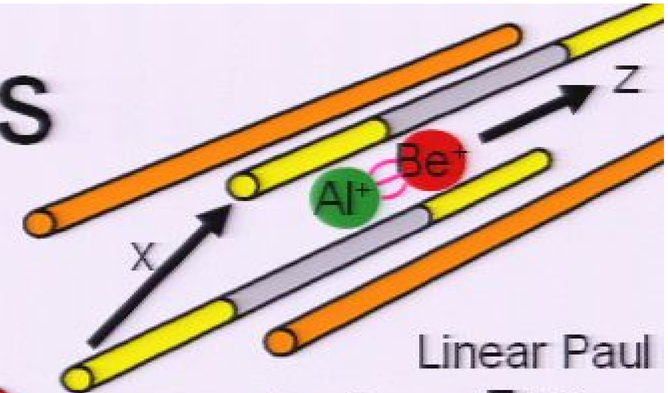
Center-of-mass (COM) 2.62 MHz





Normal modes



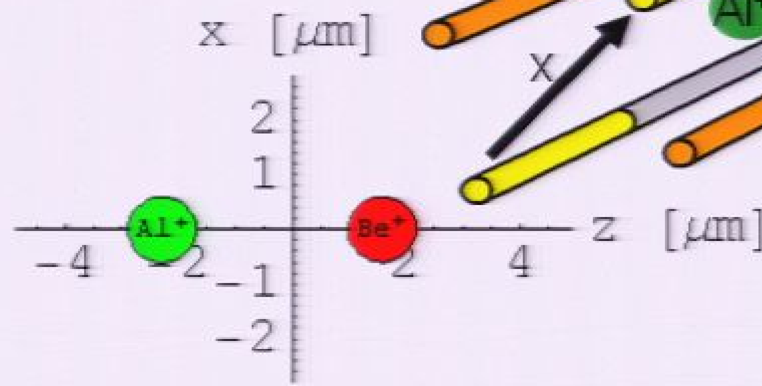


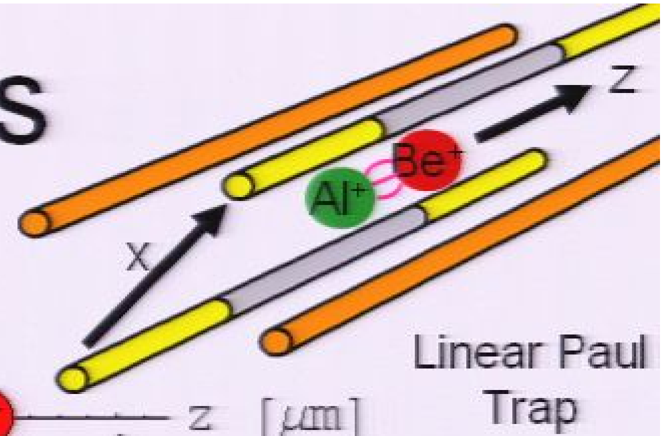
Linear Paul Trap

Center-of-mass (COM) 2.62 MHz

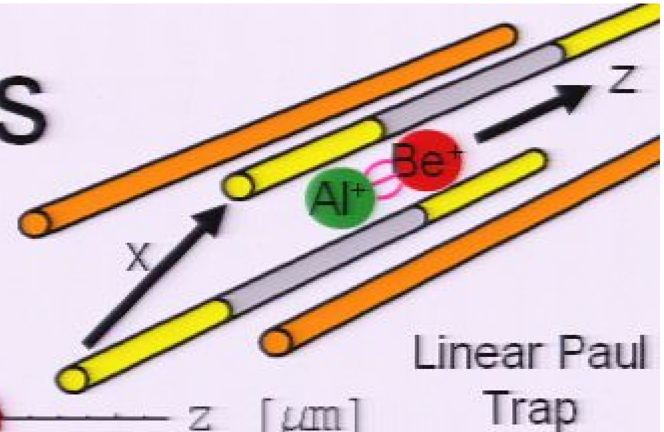
Normal modes

Center-of-mass (COM) 2.62 MHz

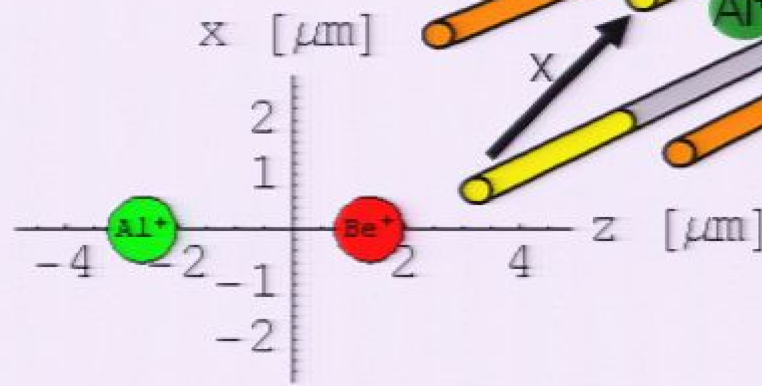




Normal modes

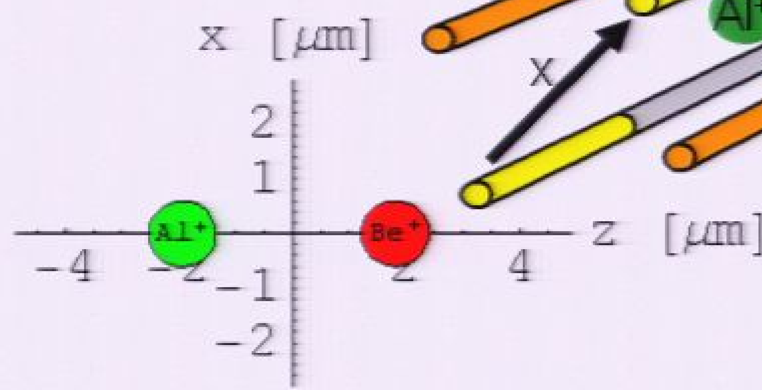


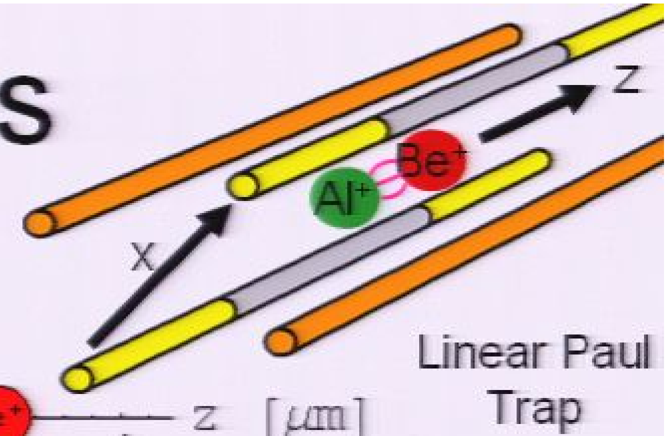
Center-of-mass (COM) 2.62 MHz



Normal modes

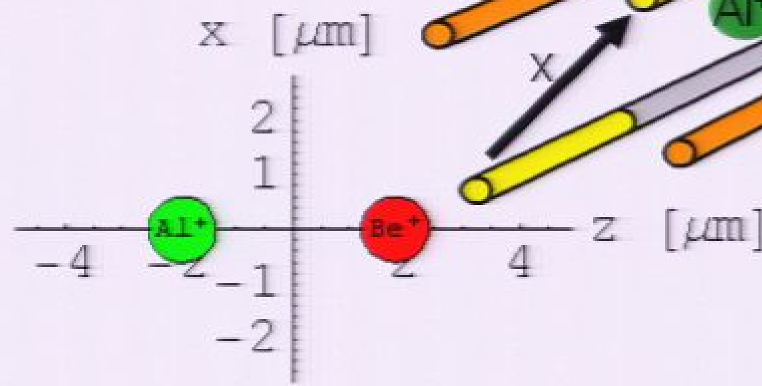
Center-of-mass (COM) 2.62 MHz

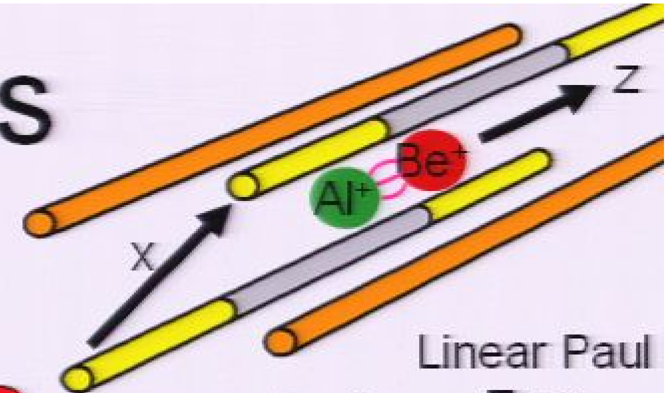




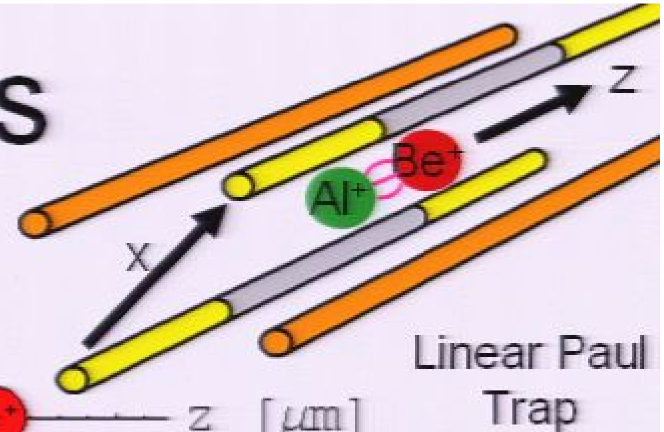
Normal modes

Center-of-mass (COM) 2.62 MHz

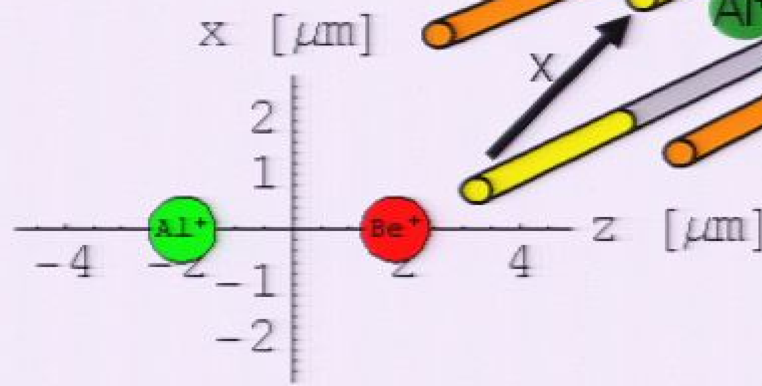




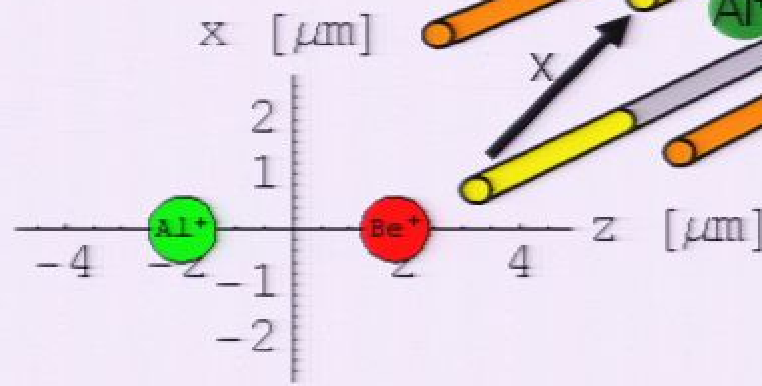
Normal modes

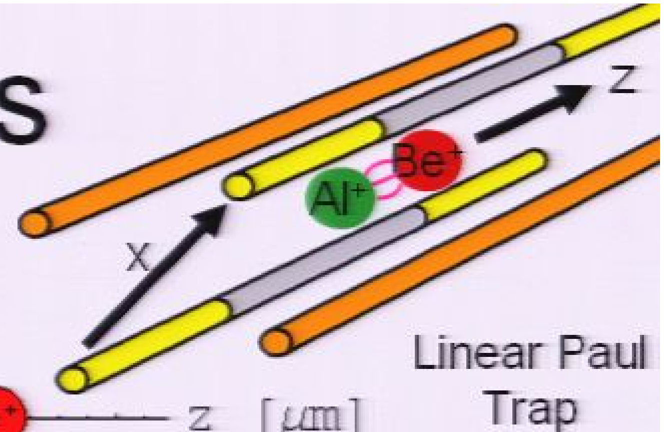


Center-of-mass (COM) 2.62 MHz



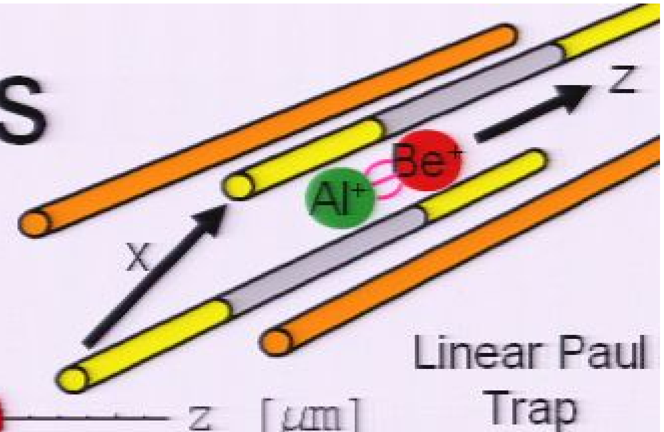
Normal modes



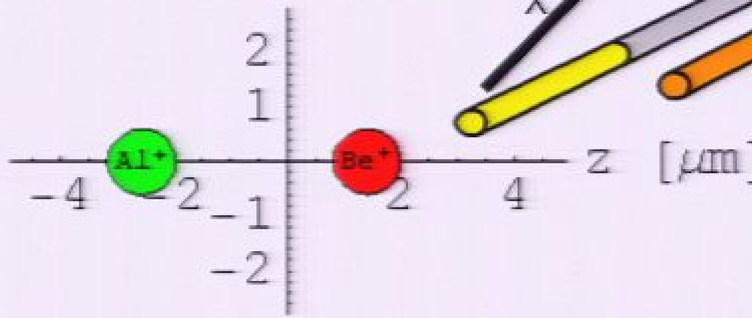


Center-of-mass (COM) 2.62 MHz

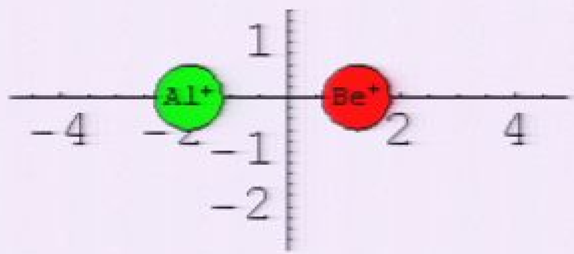
Normal modes



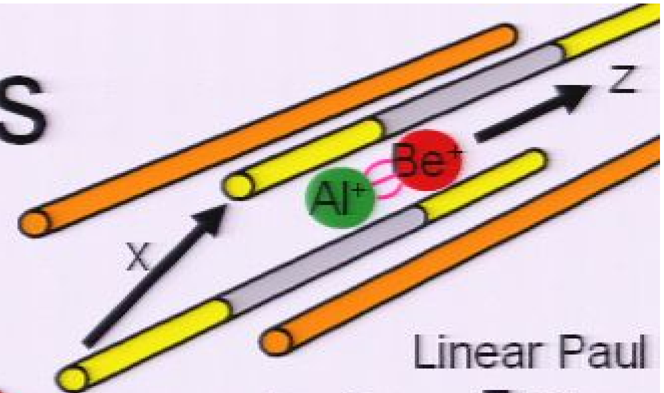
Center-of-mass (COM) 2.62 MHz



Stretch 5.8 MHz

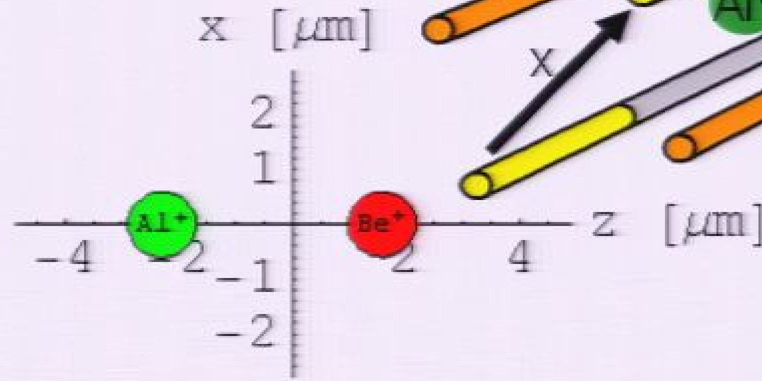


Normal modes

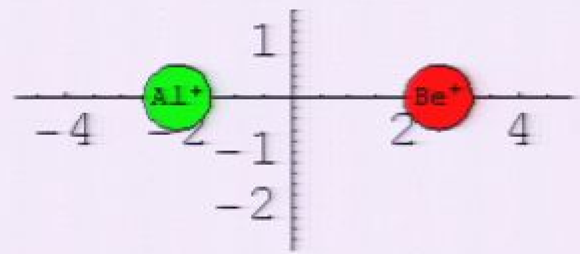


Linear Paul Trap

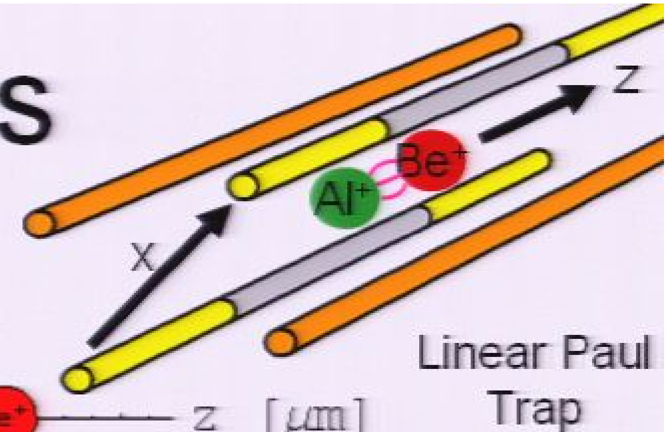
Center-of-mass (COM) 2.62 MHz



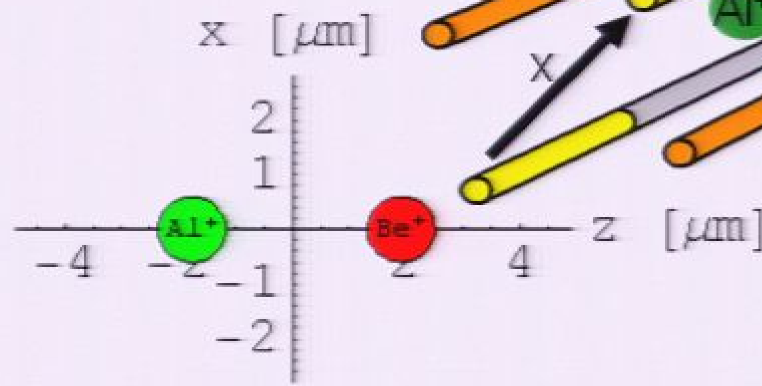
Stretch 5.8 MHz



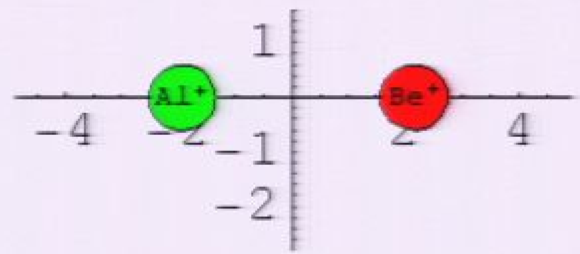
Normal modes



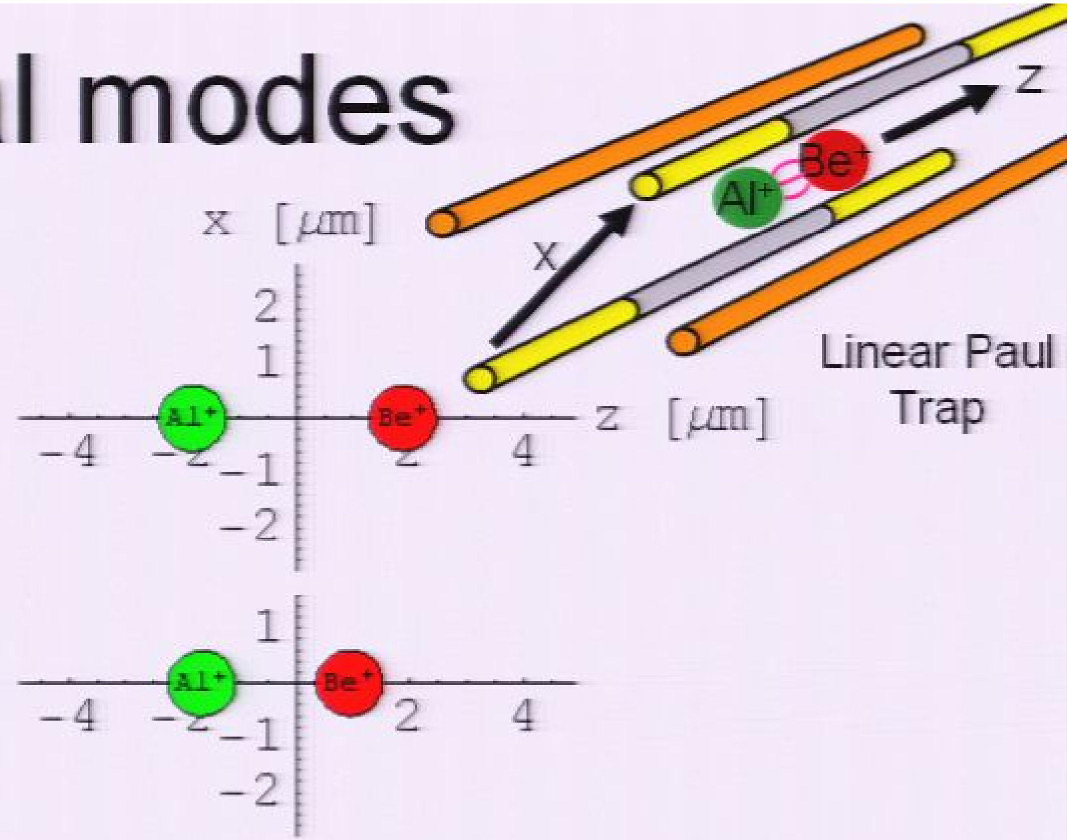
Center-of-mass (COM) 2.62 MHz



Stretch 5.8 MHz



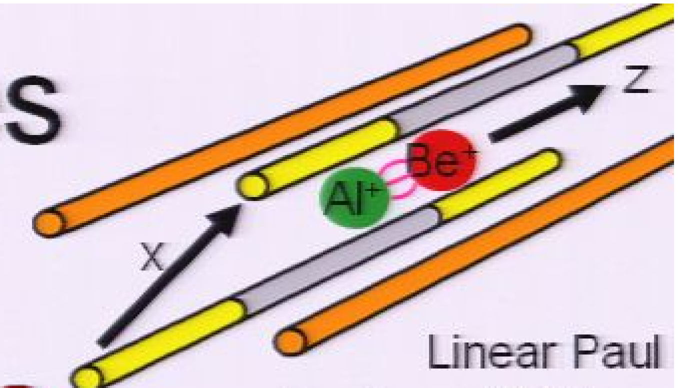
Normal modes



Center-of-mass (COM) 2.62 MHz

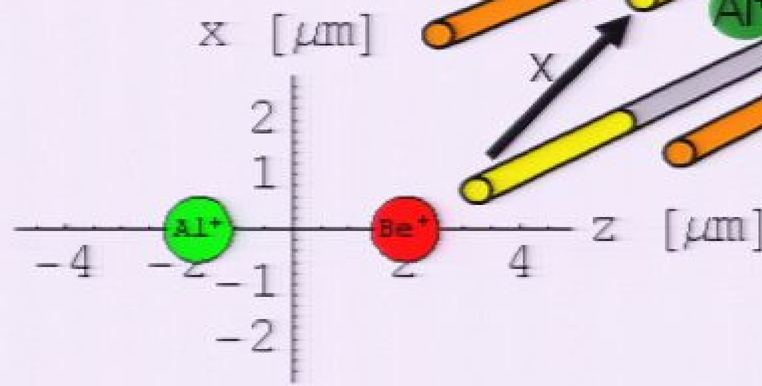
Stretch 5.8 MHz

Normal modes

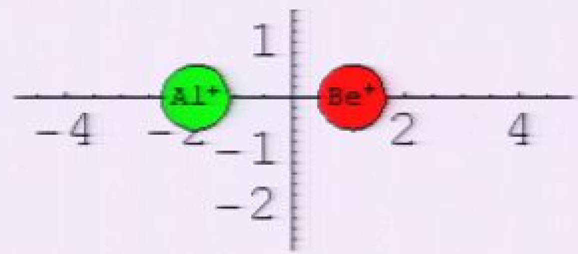


Linear Paul Trap

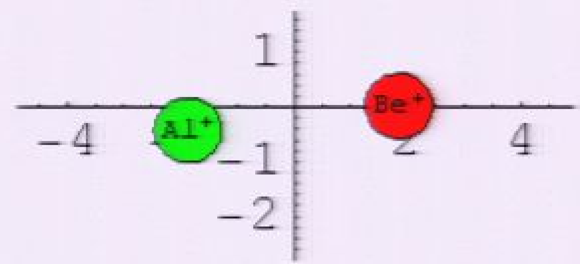
Center-of-mass (COM) 2.62 MHz



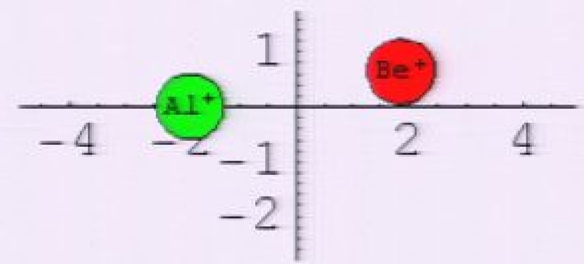
Stretch 5.8 MHz



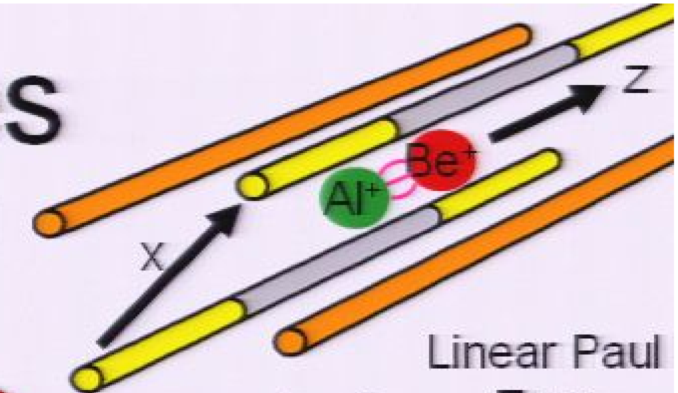
xAl 3.5 MHz



xBe 13.0 MHz

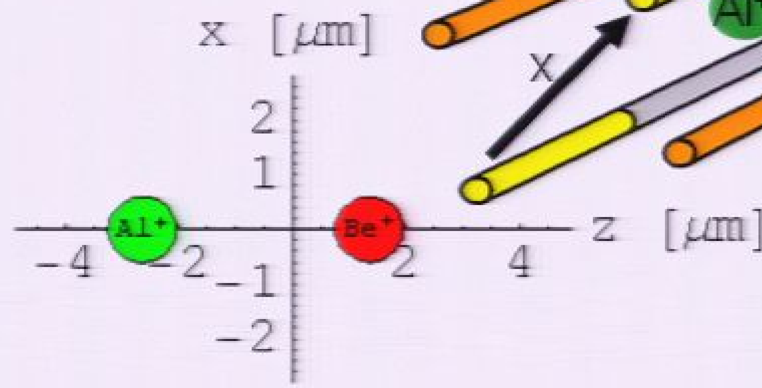


Normal modes

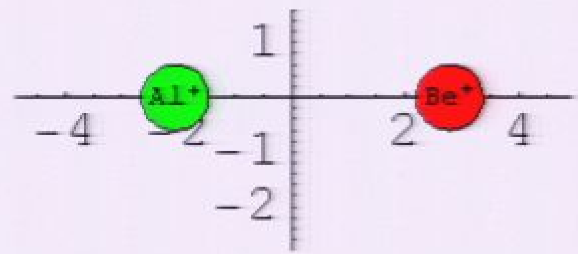


Linear Paul Trap

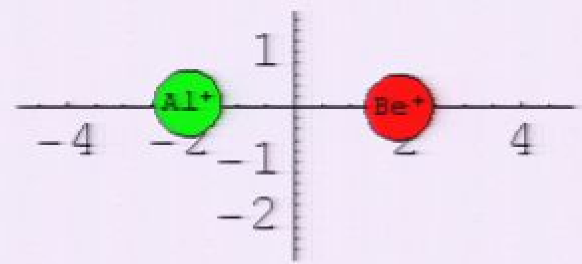
Center-of-mass (COM) 2.62 MHz



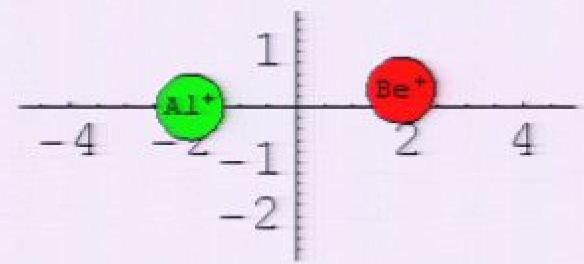
Stretch 5.8 MHz



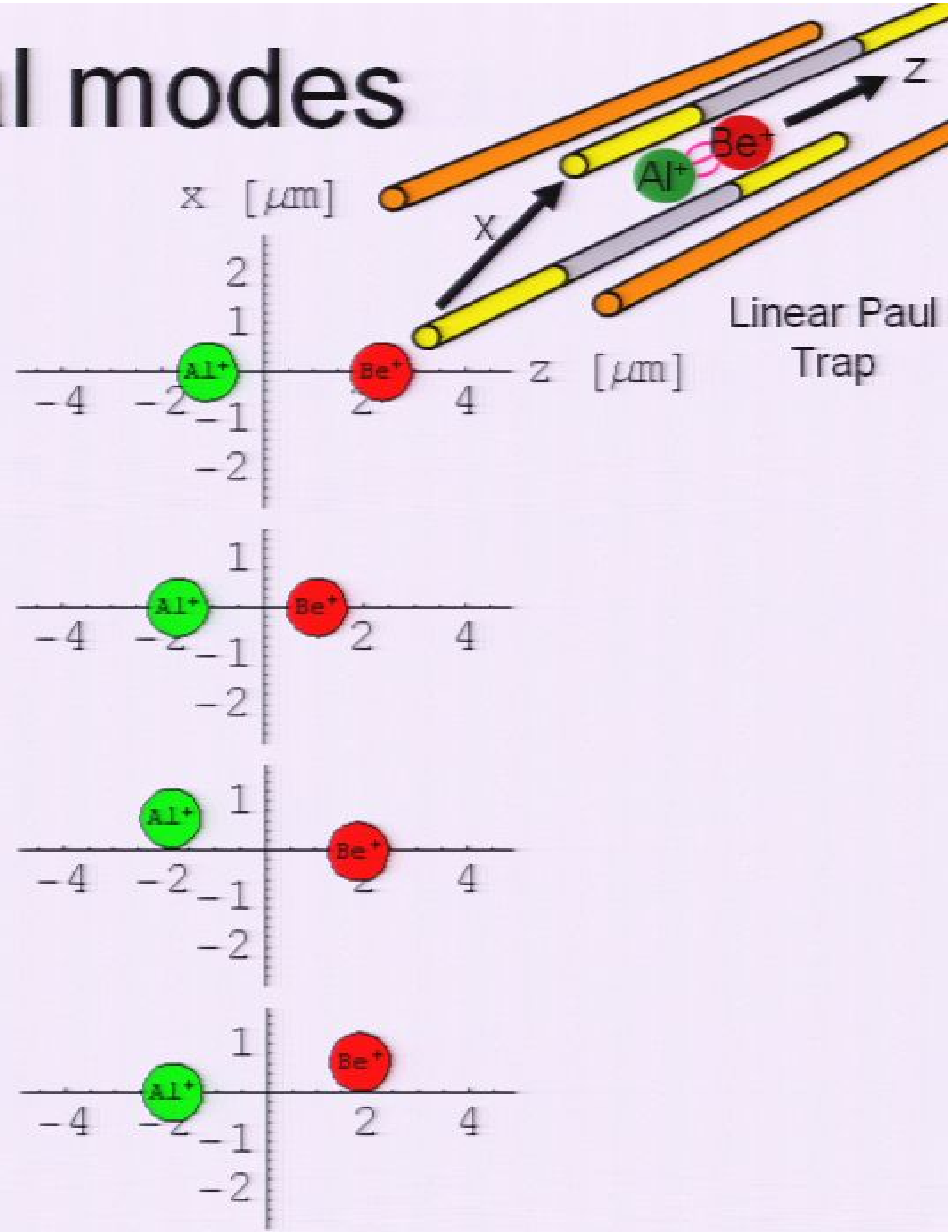
xAl 3.5 MHz



xBe 13.0 MHz



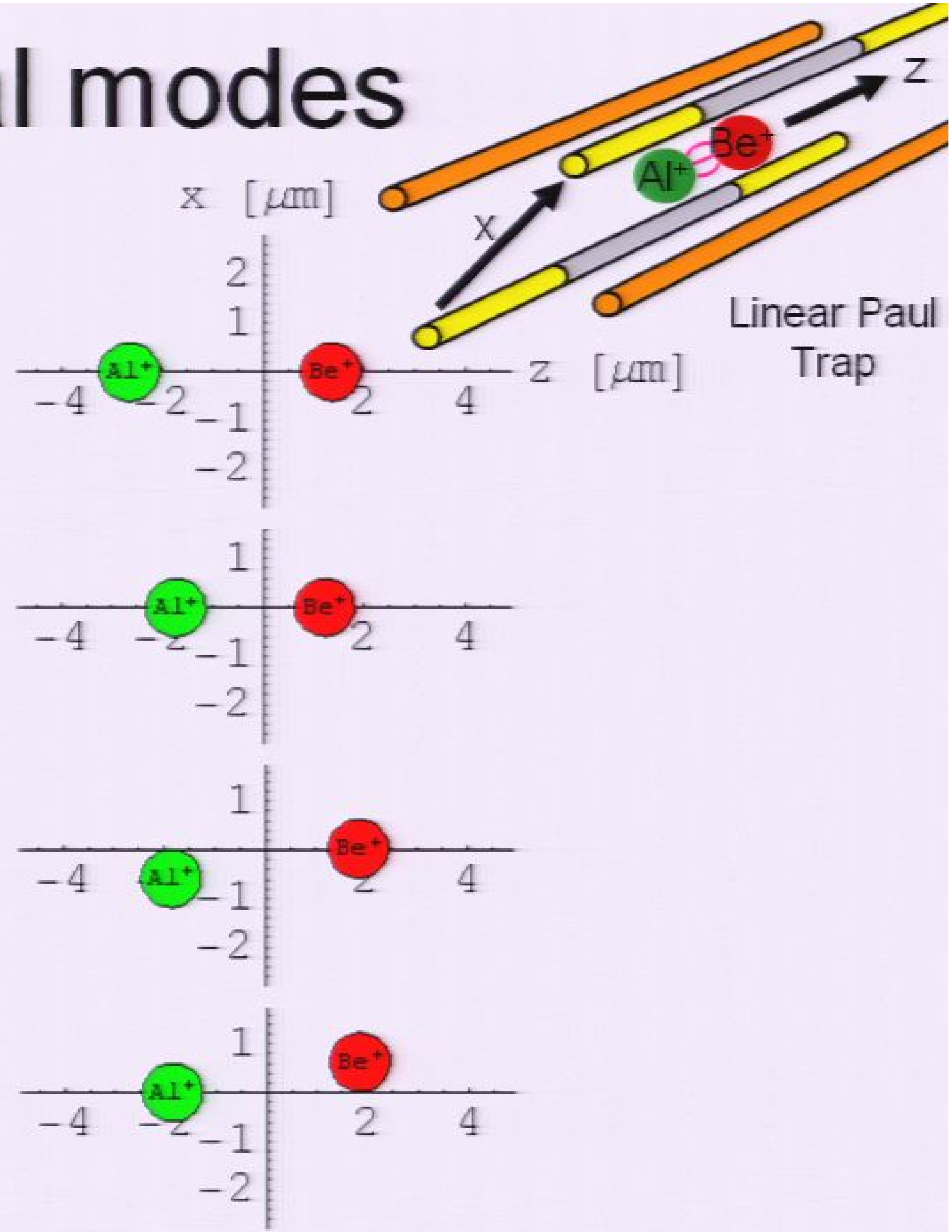
Normal modes



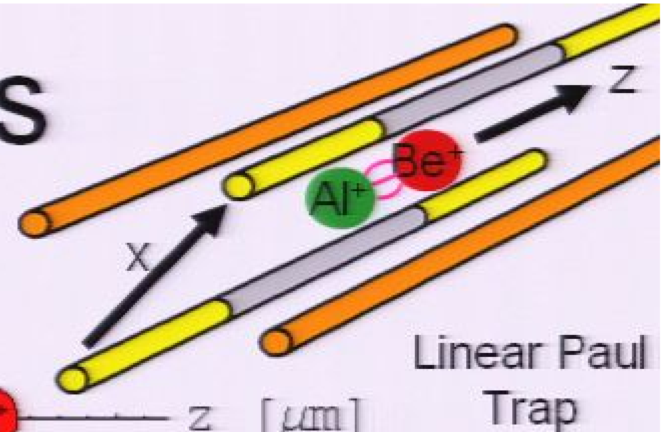
Mode	Frequency
Center-of-mass (COM)	2.62 MHz
Stretch	5.8 MHz
xAl	3.5 MHz
xBe	13.0 MHz

Normal modes

Center-of-mass (COM)	2.62 MHz
Stretch	5.8 MHz
xAl	3.5 MHz
xBe	13.0 MHz



Normal modes

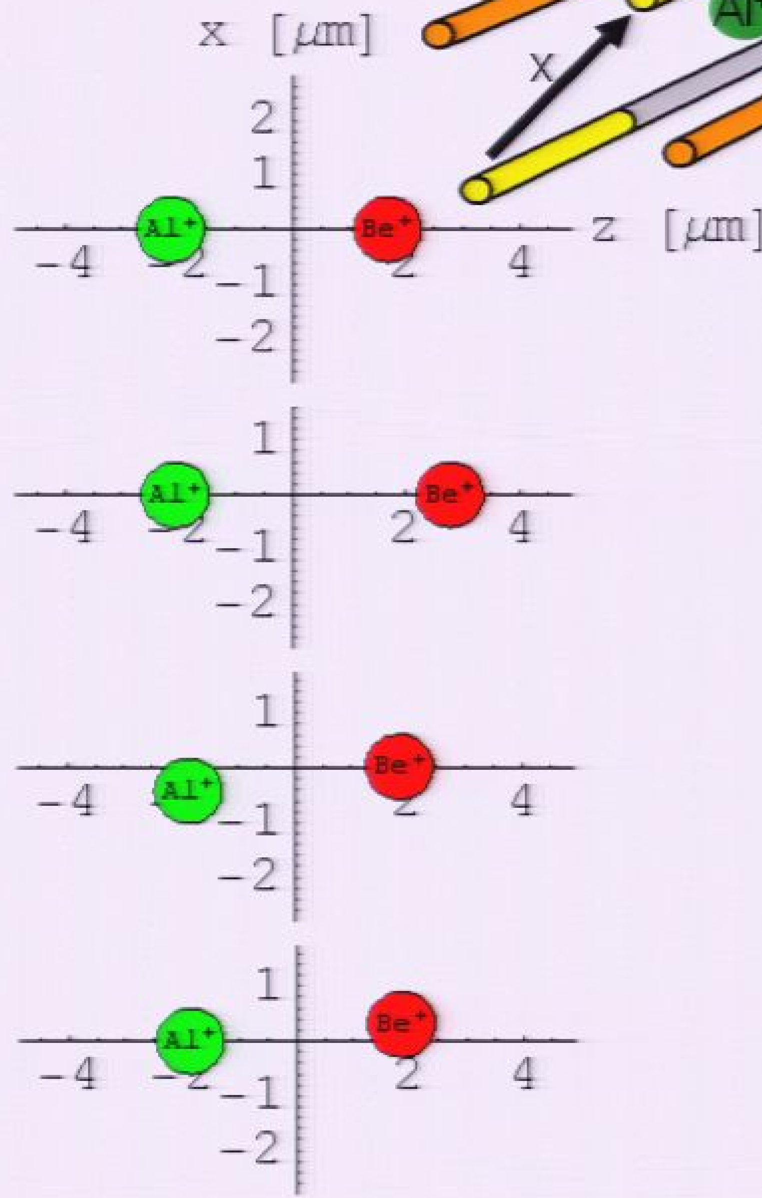


Center-of-mass (COM) 2.62 MHz

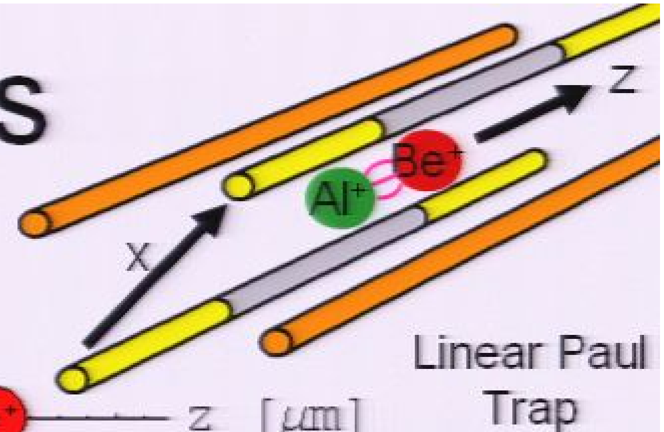
Stretch 5.8 MHz

xAl 3.5 MHz

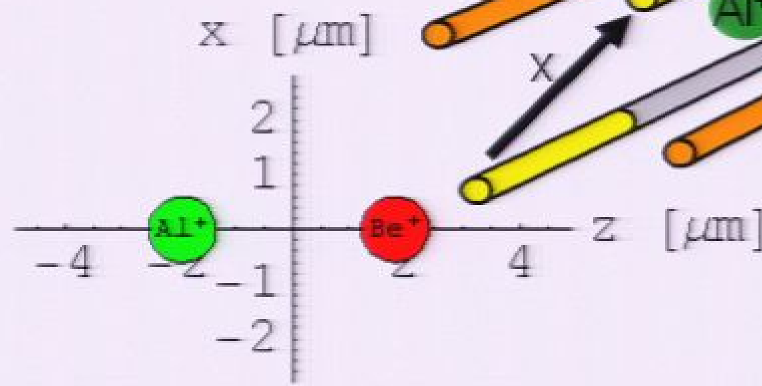
xBe 13.0 MHz



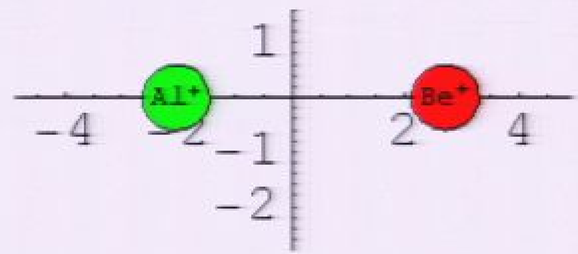
Normal modes



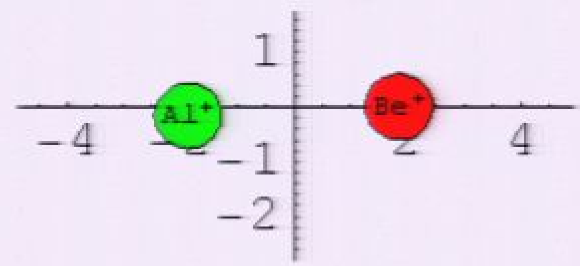
Center-of-mass (COM) 2.62 MHz



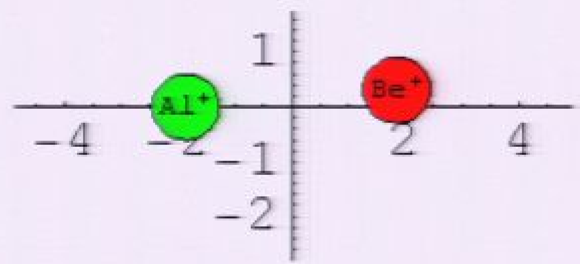
Stretch 5.8 MHz



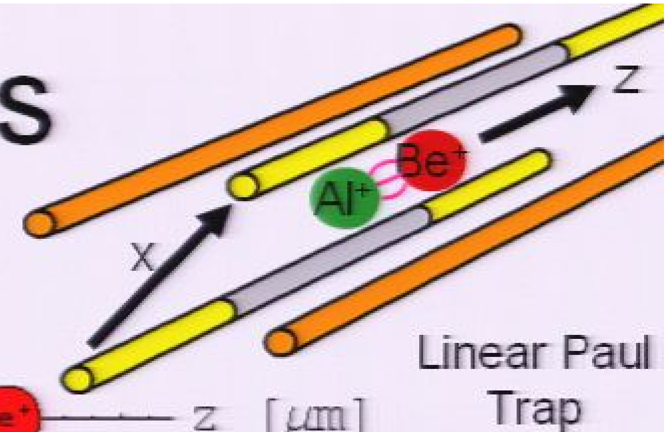
xAl 3.5 MHz



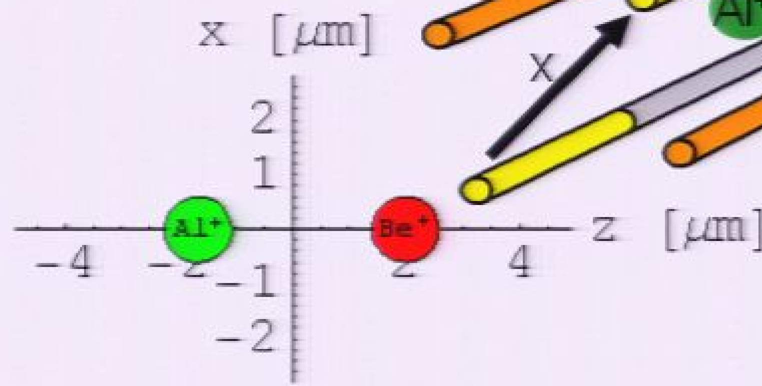
xBe 13.0 MHz



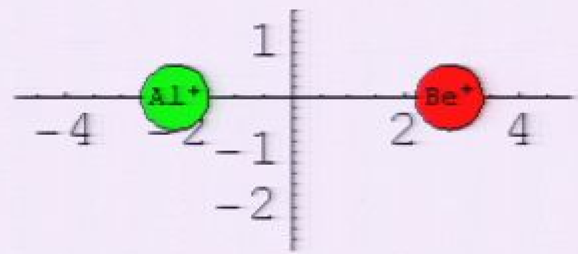
Normal modes



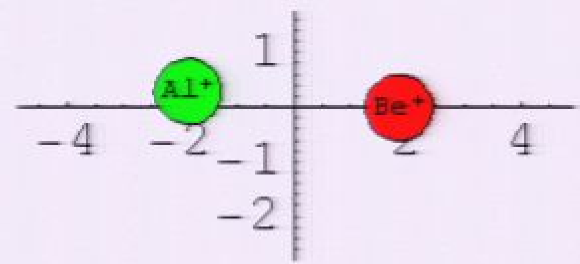
Center-of-mass (COM) 2.62 MHz



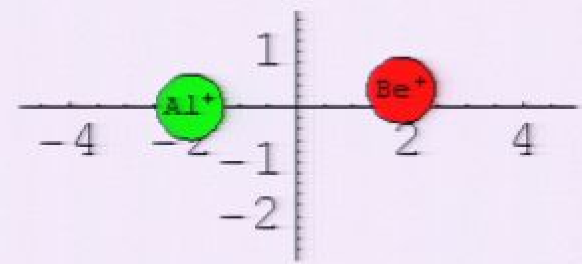
Stretch 5.8 MHz



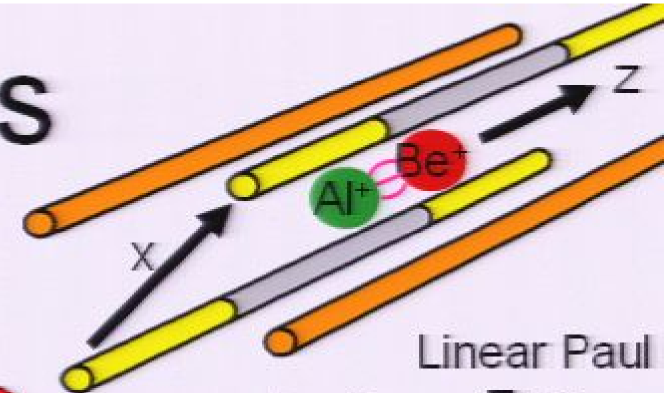
xAl 3.5 MHz



xBe 13.0 MHz

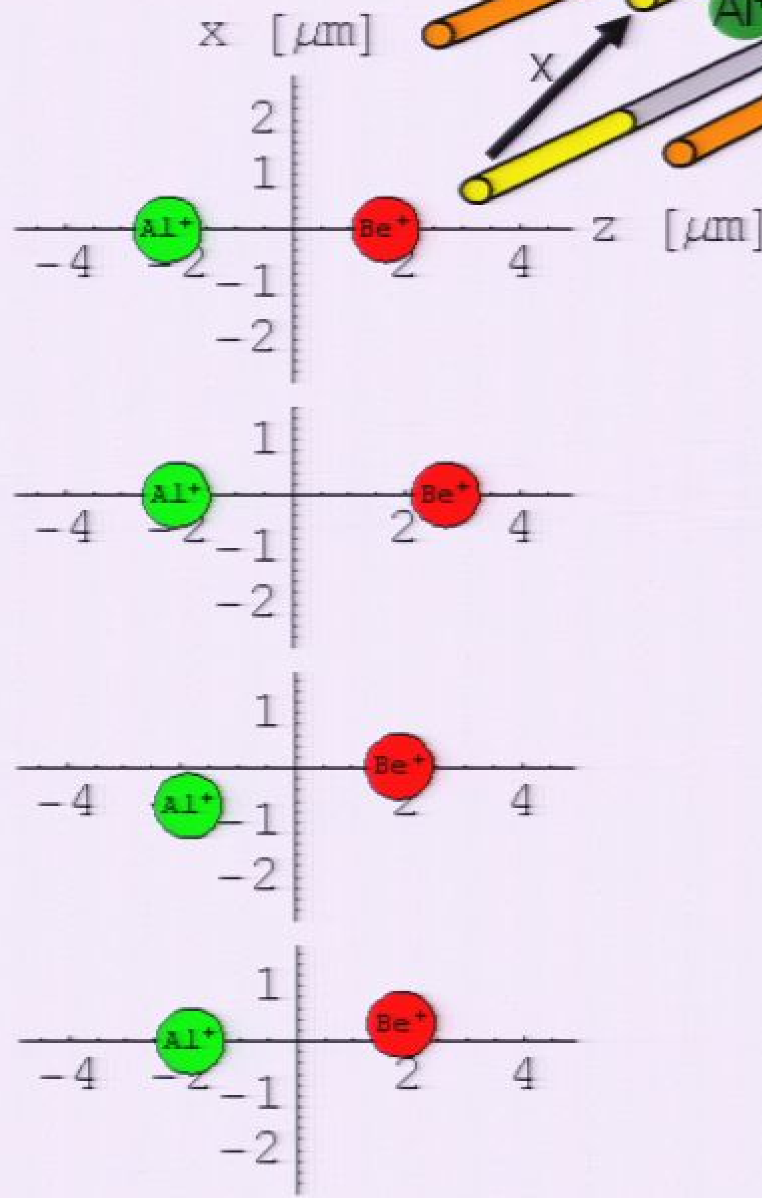


Normal modes



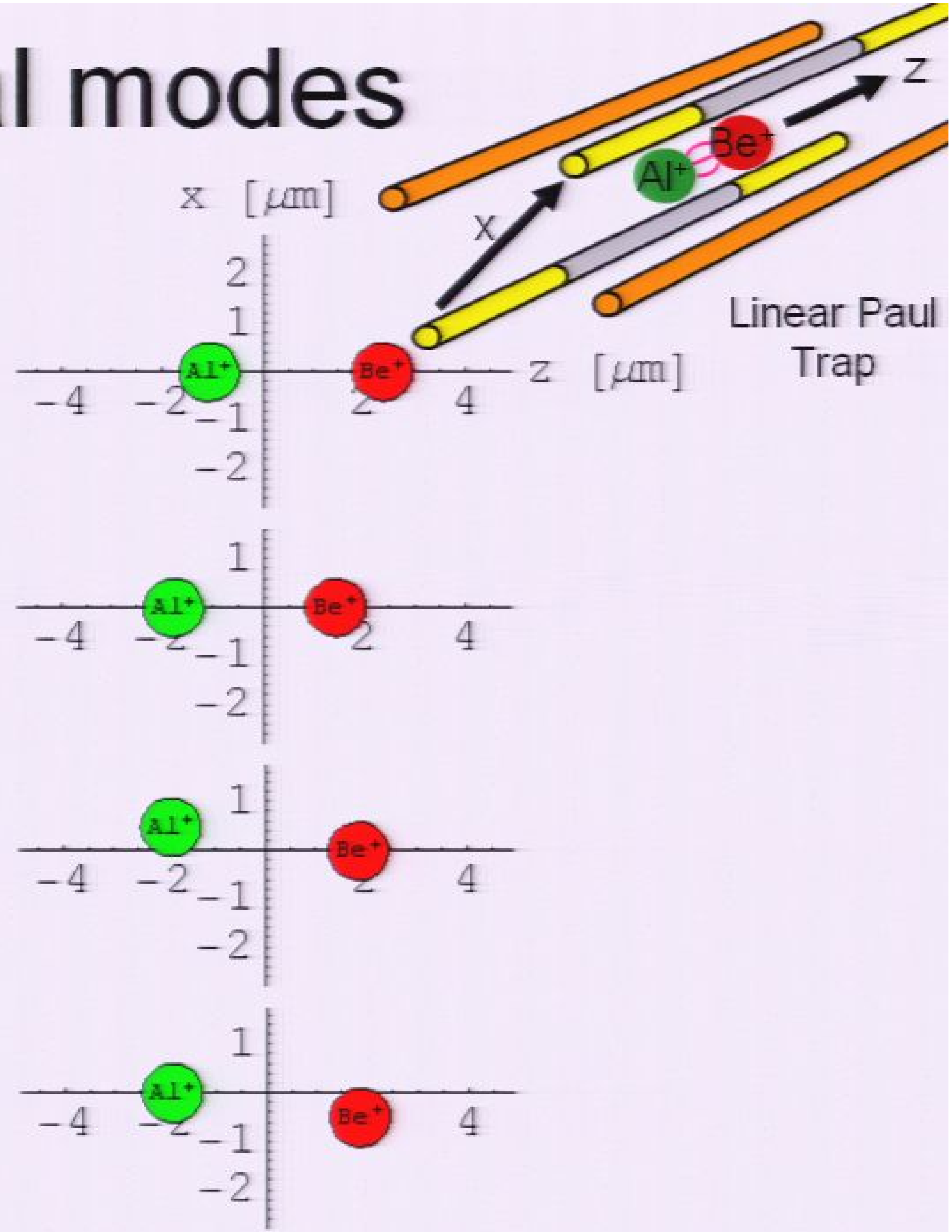
Linear Paul Trap

Center-of-mass (COM)	2.62 MHz
Stretch	5.8 MHz
xAl	3.5 MHz
xBe	13.0 MHz

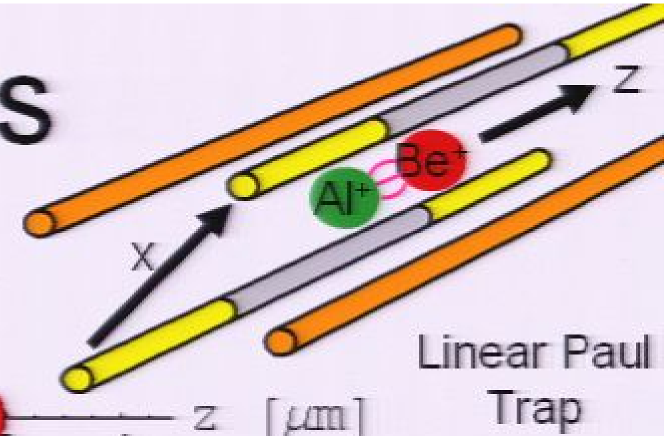


Normal modes

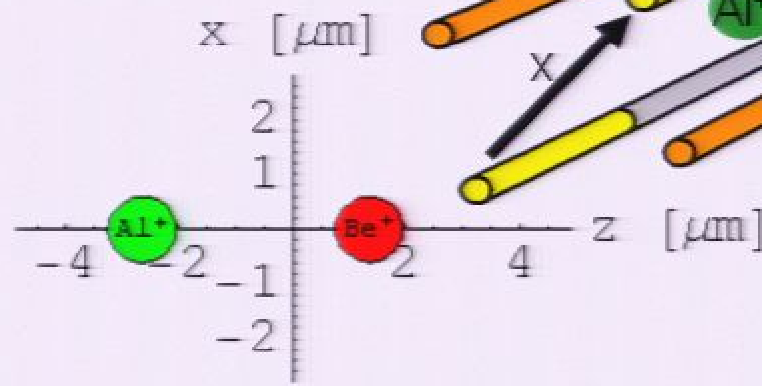
Center-of-mass (COM)	2.62 MHz
Stretch	5.8 MHz
xAl	3.5 MHz
xBe	13.0 MHz



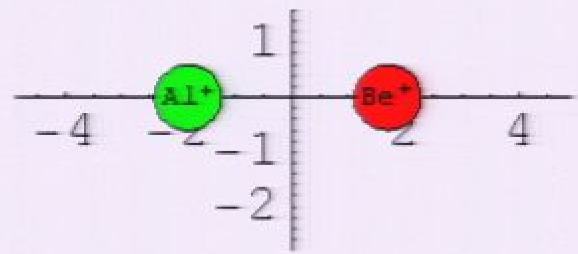
Normal modes



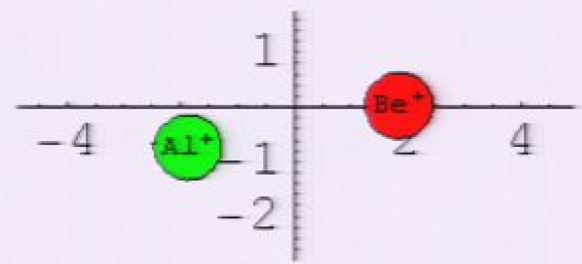
Center-of-mass (COM) 2.62 MHz



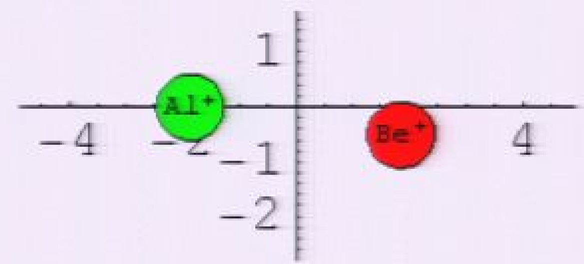
Stretch 5.8 MHz



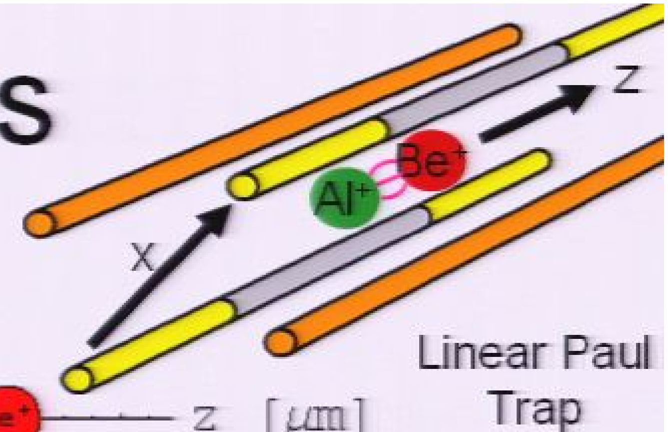
xAl 3.5 MHz



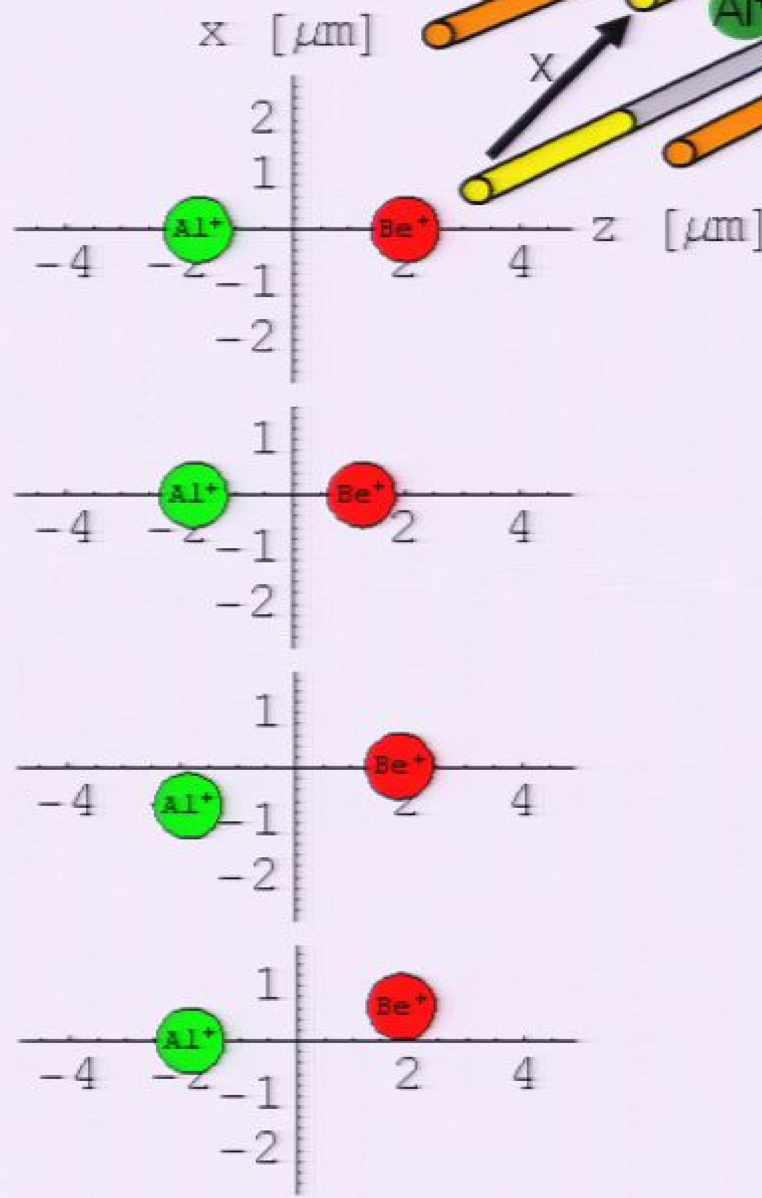
xBe 13.0 MHz



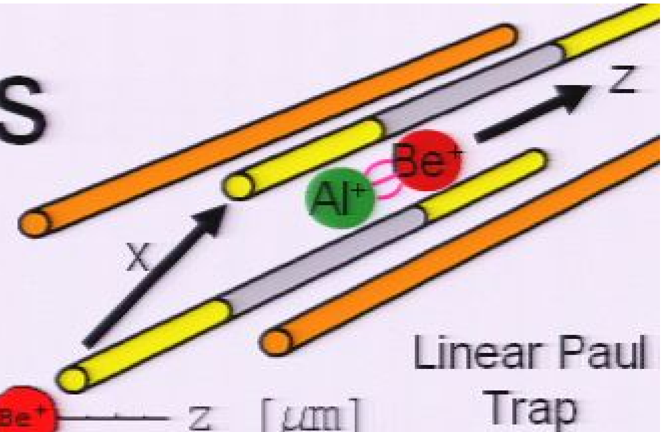
Normal modes

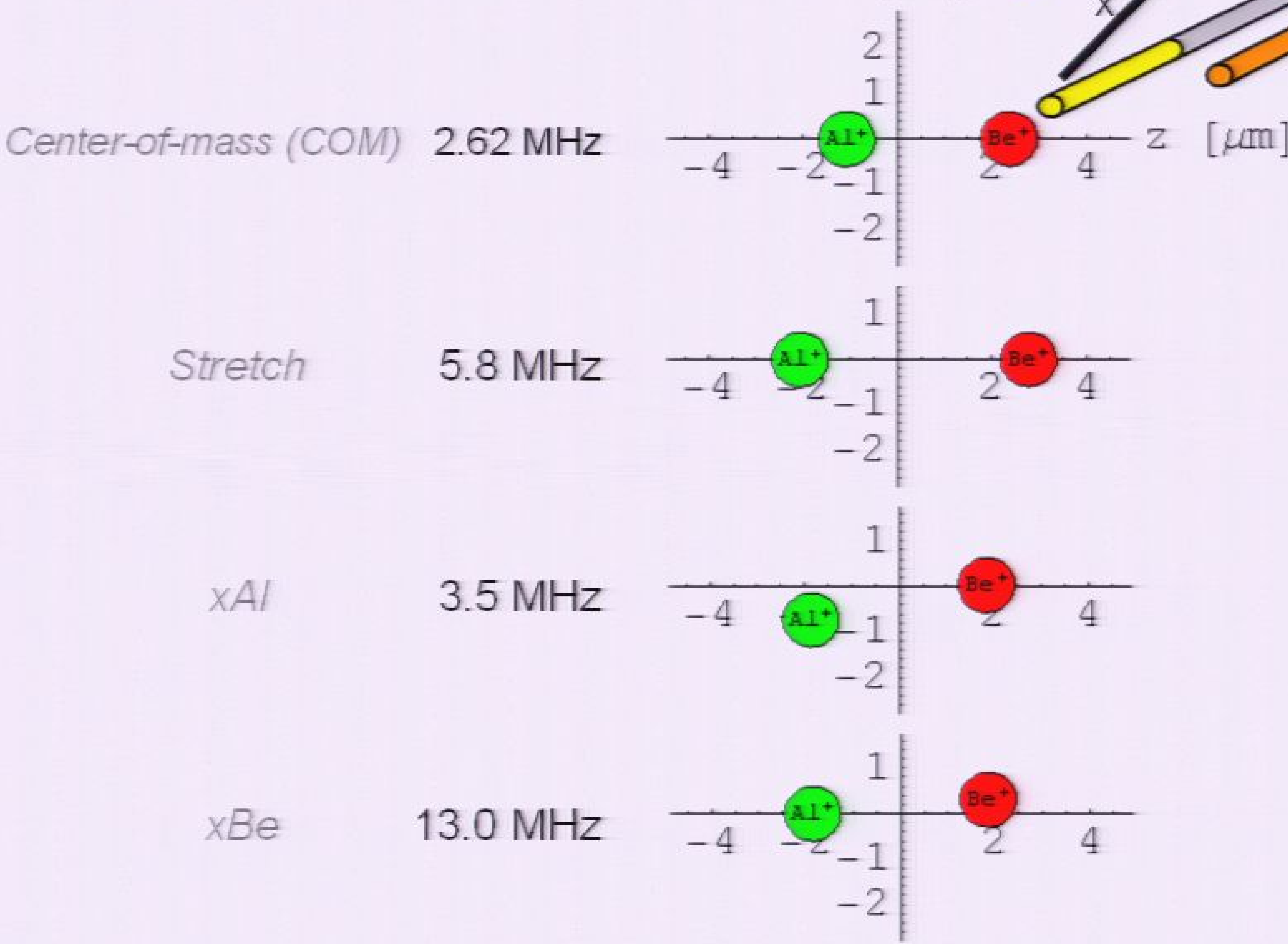


Mode	Frequency
Center-of-mass (COM)	2.62 MHz
Stretch	5.8 MHz
xAl	3.5 MHz
xBe	13.0 MHz

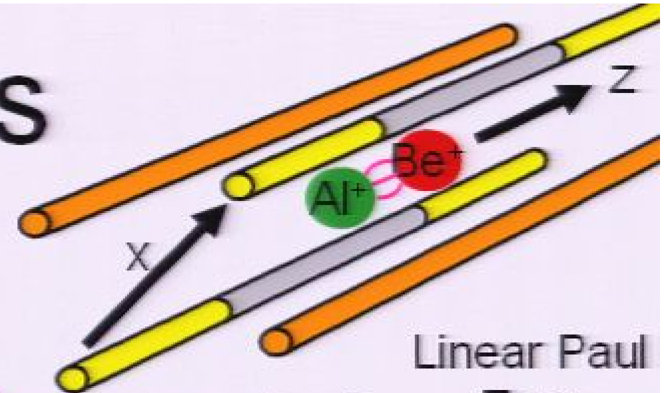


Normal modes



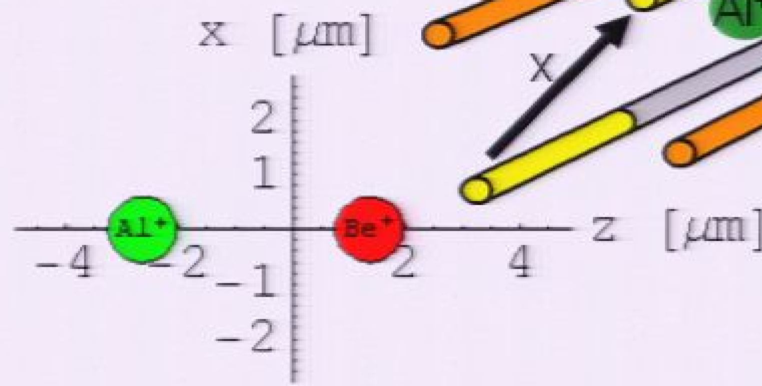


Normal modes

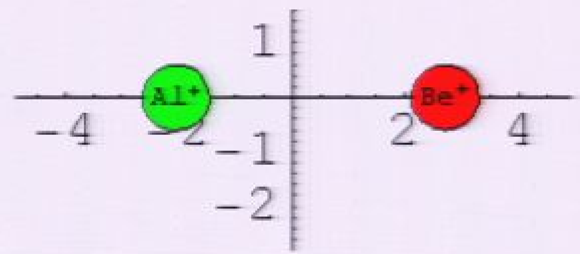


Linear Paul Trap

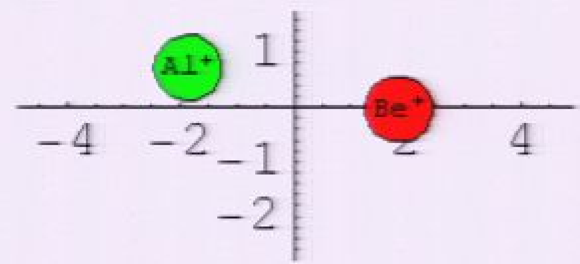
Center-of-mass (COM) 2.62 MHz



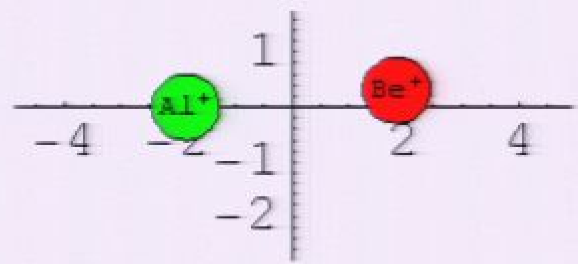
Stretch 5.8 MHz



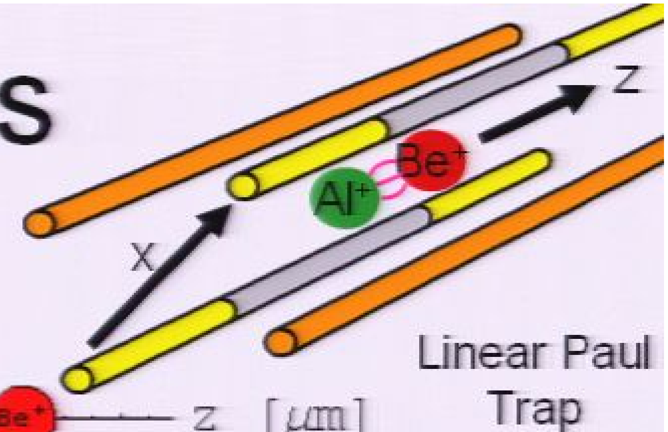
xAl 3.5 MHz



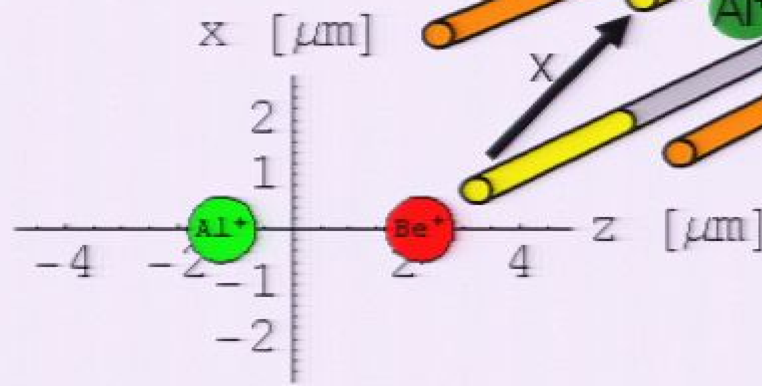
xBe 13.0 MHz



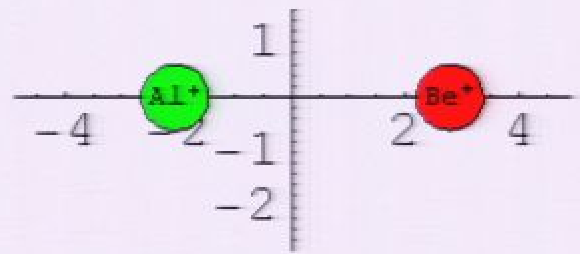
Normal modes



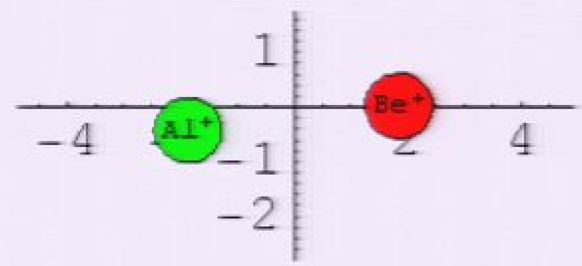
Center-of-mass (COM) 2.62 MHz



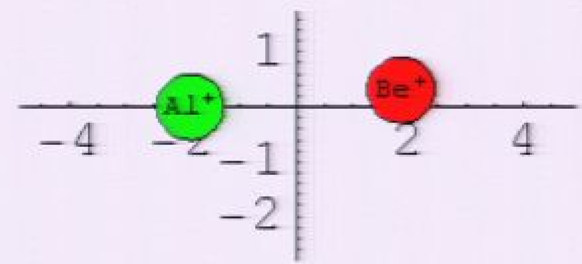
Stretch 5.8 MHz



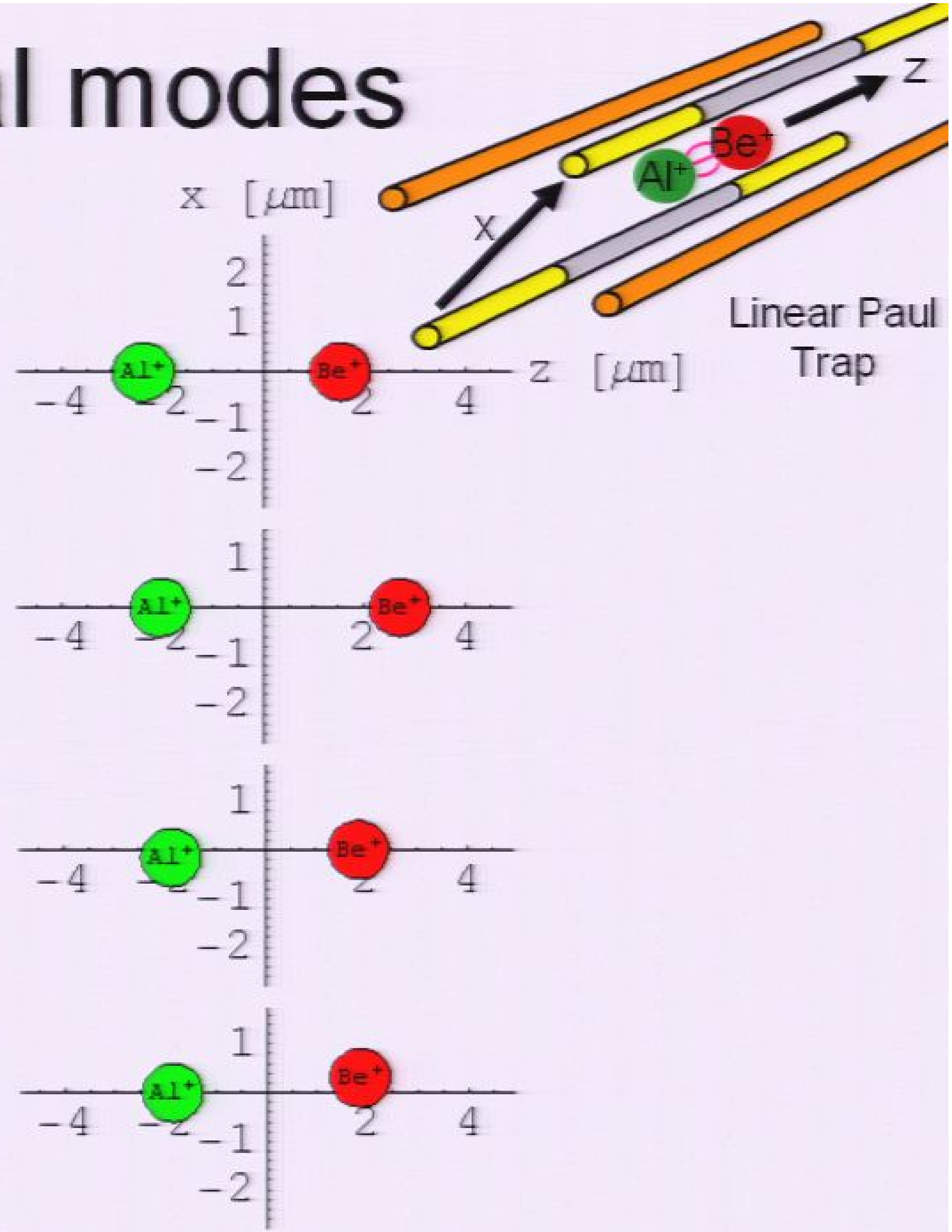
xAl 3.5 MHz



xBe 13.0 MHz



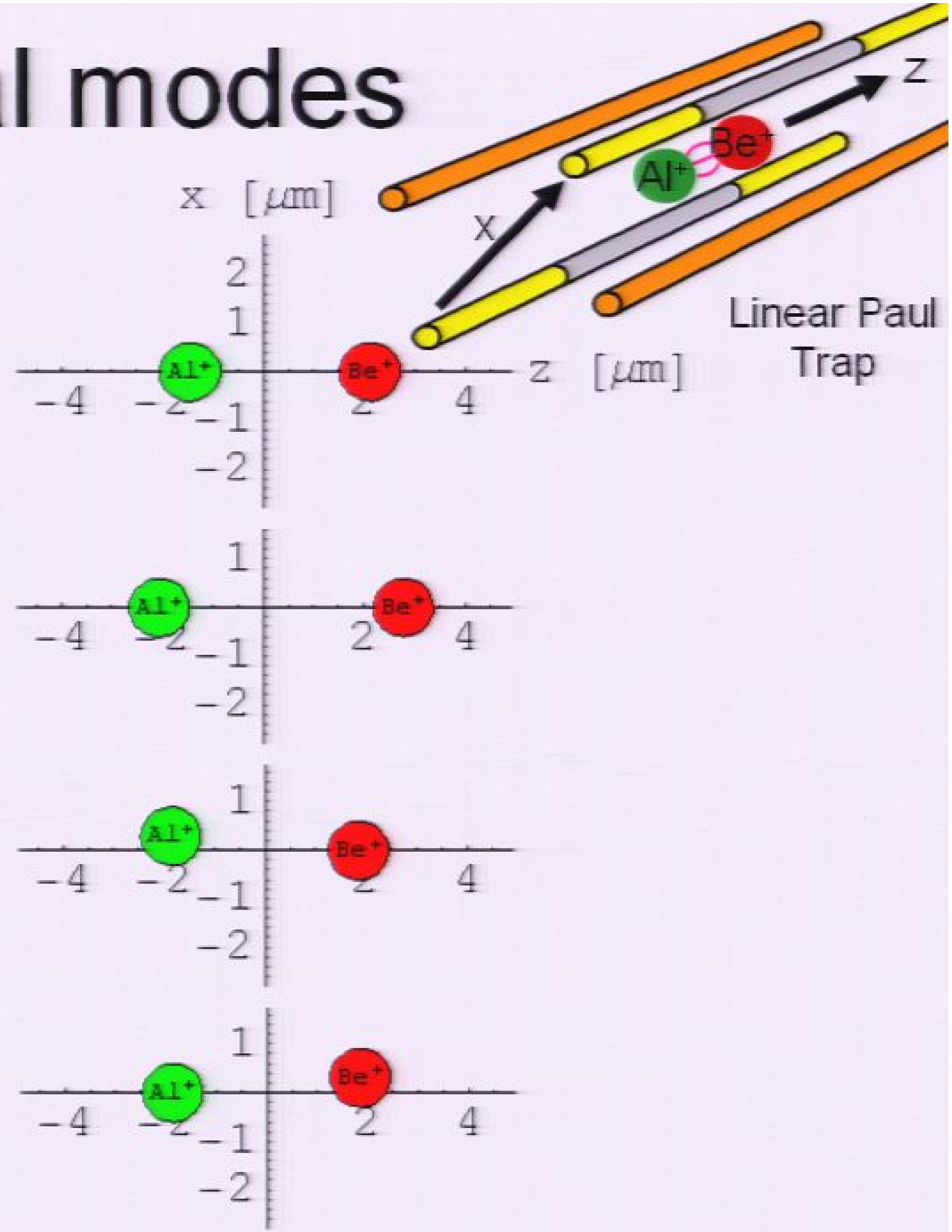
Normal modes



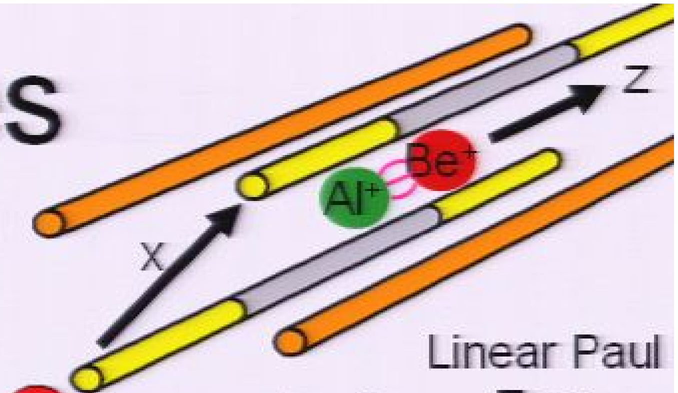
Center-of-mass (COM)	2.62 MHz
Stretch	5.8 MHz
xAl	3.5 MHz
xBe	13.0 MHz

Normal modes

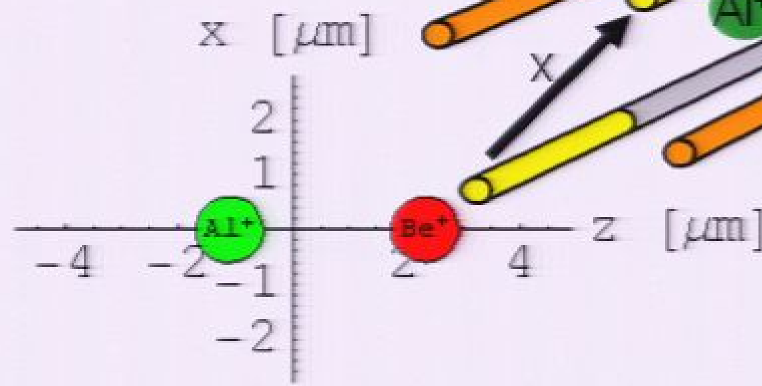
Center-of-mass (COM)	2.62 MHz
Stretch	5.8 MHz
xAl	3.5 MHz
xBe	13.0 MHz



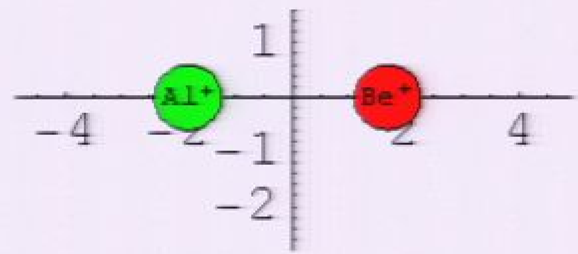
Normal modes



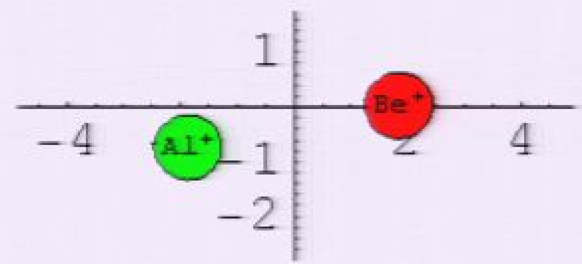
Center-of-mass (COM) 2.62 MHz



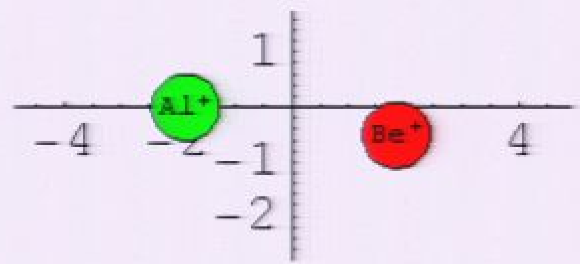
Stretch 5.8 MHz

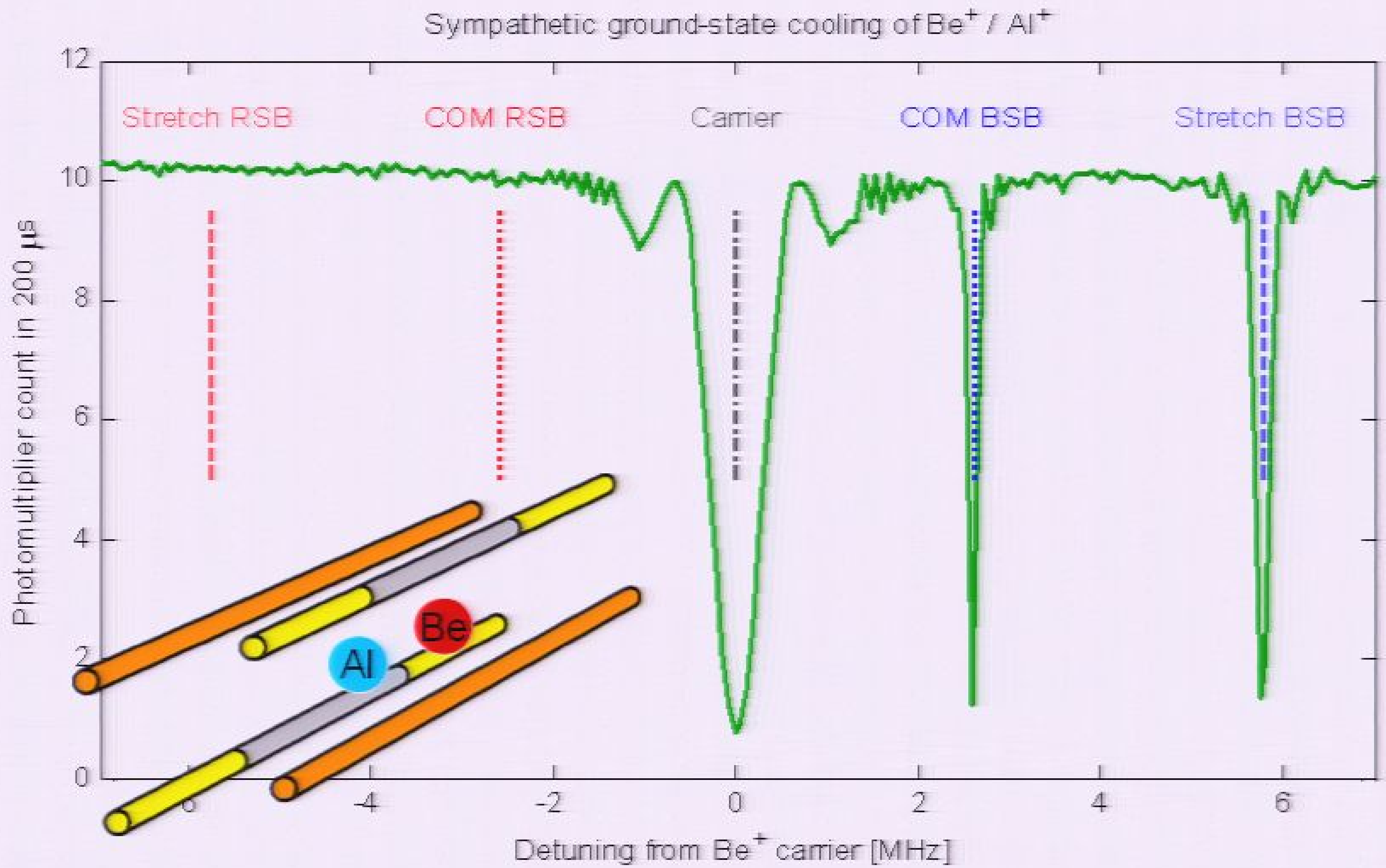


xAl 3.5 MHz



xBe 13.0 MHz





- M. Barrett *et al.* "Sympathetic cooling of $^9Be^+$ and $^{24}Mg^+$ for quantum logic," Phys. Rev. A **68**, 042302 (2003)
- Doppler cooling: <n> ≤ 4 for all six normal modes (0.5 ms)
- Raman cooling: <n> ≤ 0.01 for both axial modes (0.5 ms)

Clock state transfer to Be^+

(simplified)

1. Cool to motional quantum ground state with Be^+
2. Depending on clock state, add vibrational energy via Al^+
3. Detect vibrational energy via Be^+

Clock state transfer to Be^+ (simplified)

1. Cool to motional quantum ground state with Be^+
2. Depending on clock state, add vibrational energy via Al^+
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Clock state transfer to Be^+ (simplified)

1. Cool to motional quantum ground state with Be^+
2. Depending on clock state, add vibrational energy via Al^+
3. Detect vibrational energy via Be^+

PHYSICAL REVIEW A VOLUME 42, NUMBER 5 1 SEPTEMBER 1990

Quantum-limited cooling and detection of radio-frequency oscillations by laser-cooled ions

D. J. Heinzen and D. J. Wineland
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303
(Received 13 March 1990)

A single trapped ion, laser cooled into its quantum ground state of motion, may be used as a very-low-temperature detector of radio-frequency signals applied to the trap end caps. If the signal

$^1S_0$, n = 0

Quantum Logic Spectroscopy

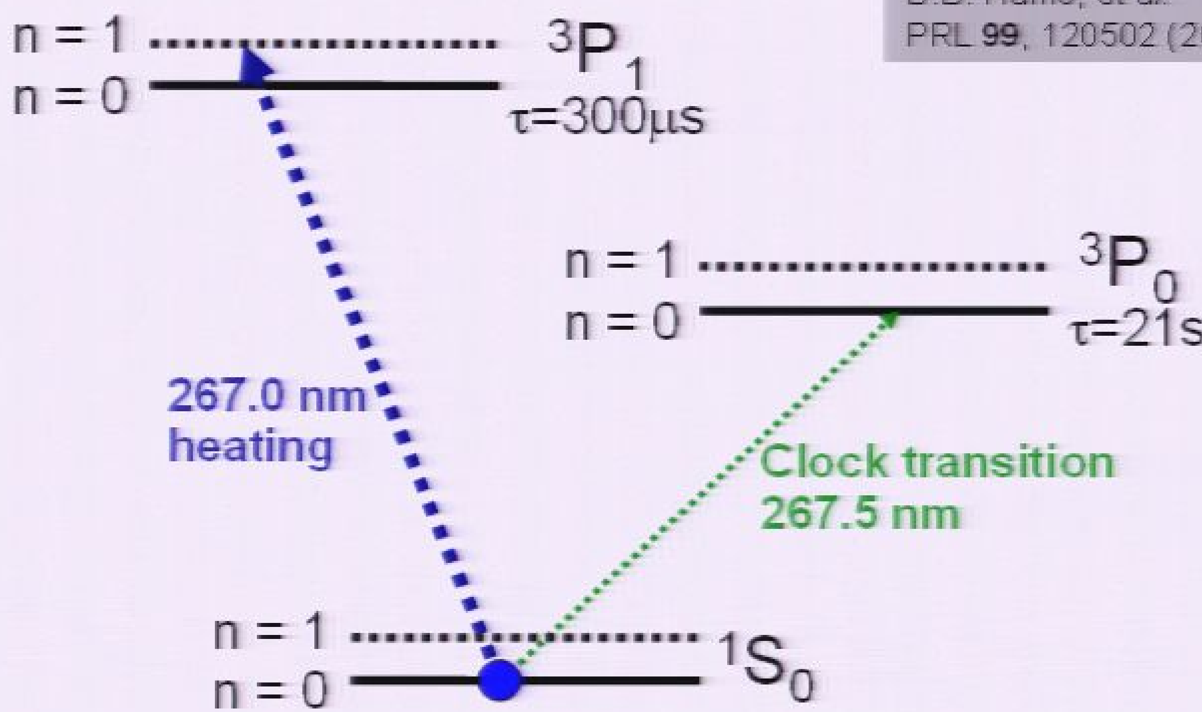
$^{27}Al^+$

D.J. Wineland, *et al.* *Proc. 6th Symp. Freq. Stds. and Metr. (2001)*

P.O. Schmidt, *et al.* *Science* **309**, 749 (2005)

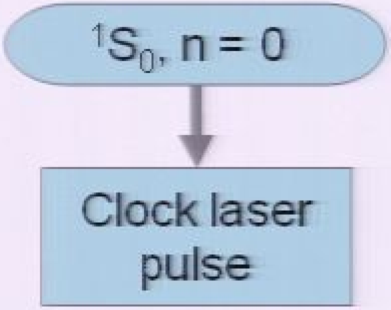
T. Rosenband, *et al.* PRL **98**, 220801 (2007)

D.B. Hume, *et al.* PRL **99**, 120502 (2007)



Quantum Logic Spectroscopy

$^{27}Al^+$



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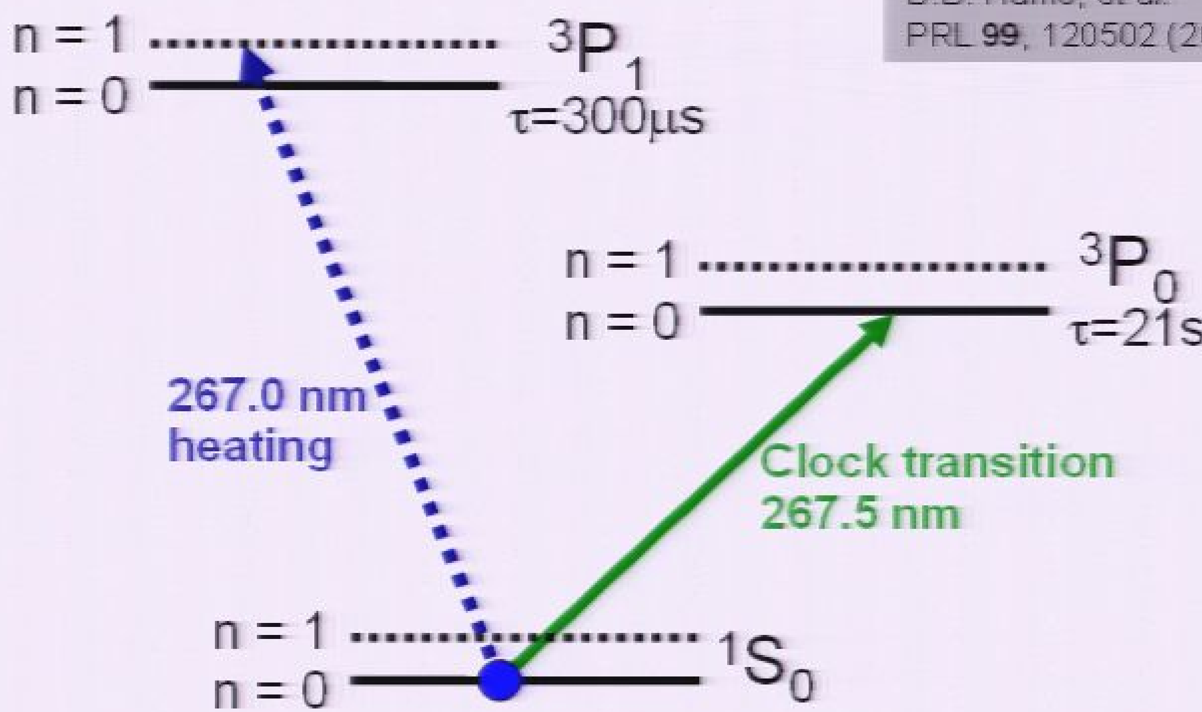
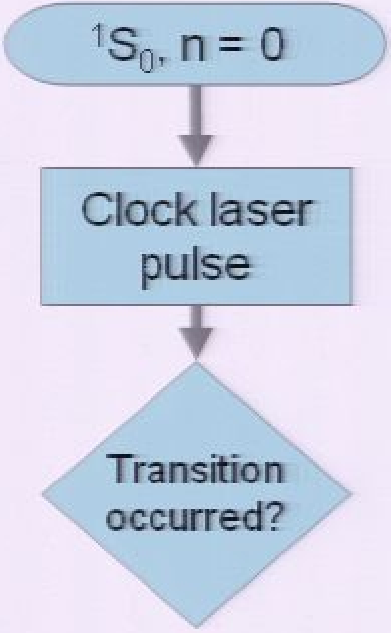


Quantum Logic Spectroscopy

$^{27}Al^+$



D.J. Wineland, *et al.* *Proc. 6th Symp. Freq. Stds. and Metr.* (2001)

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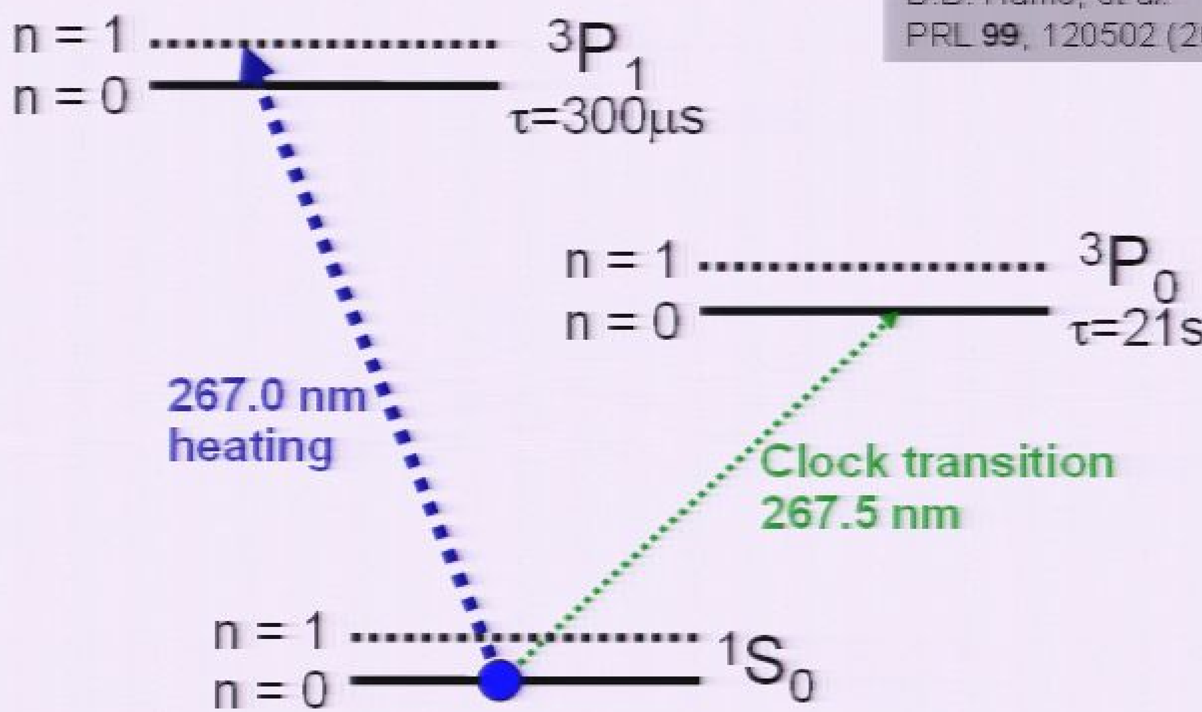

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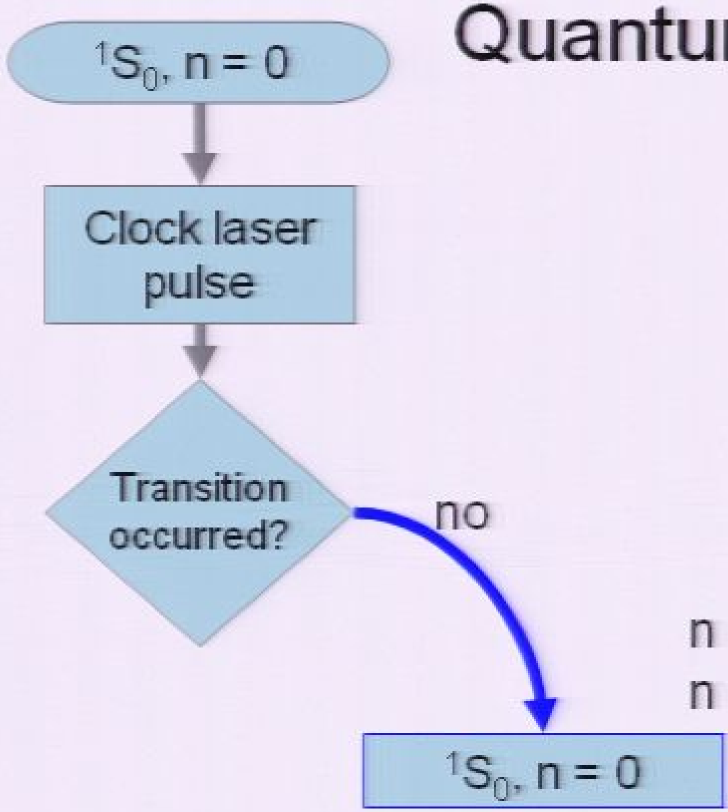

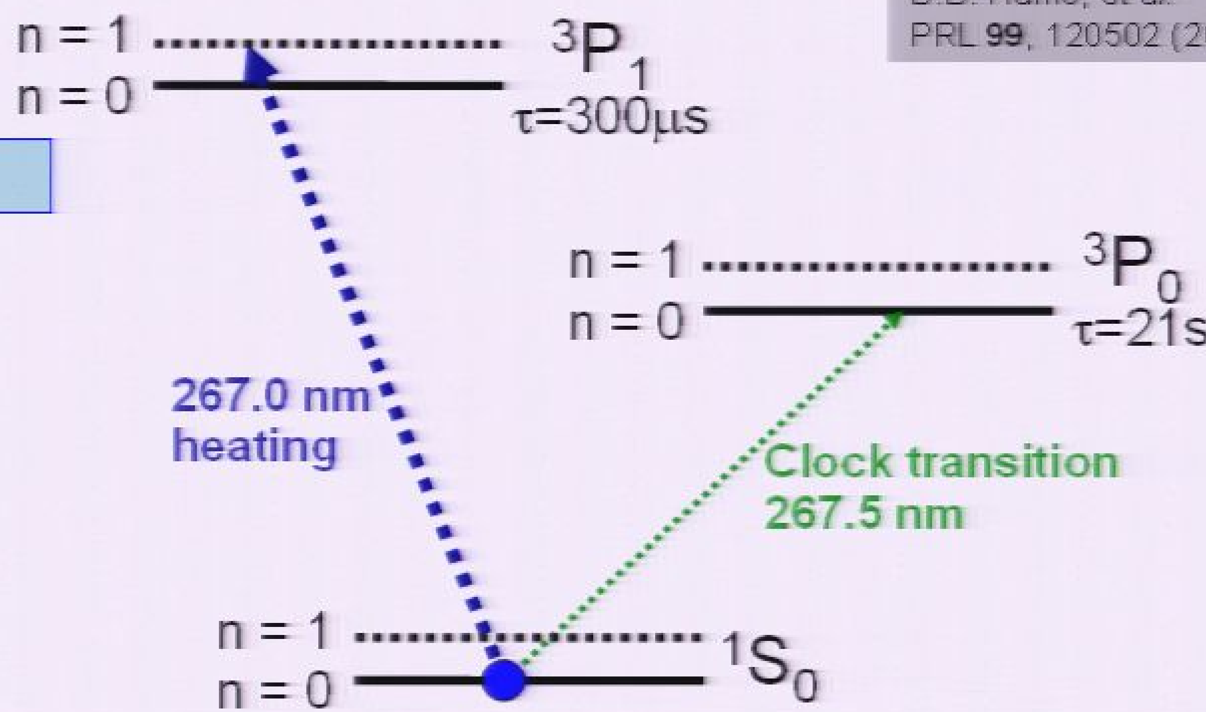

Quantum Logic Spectroscopy

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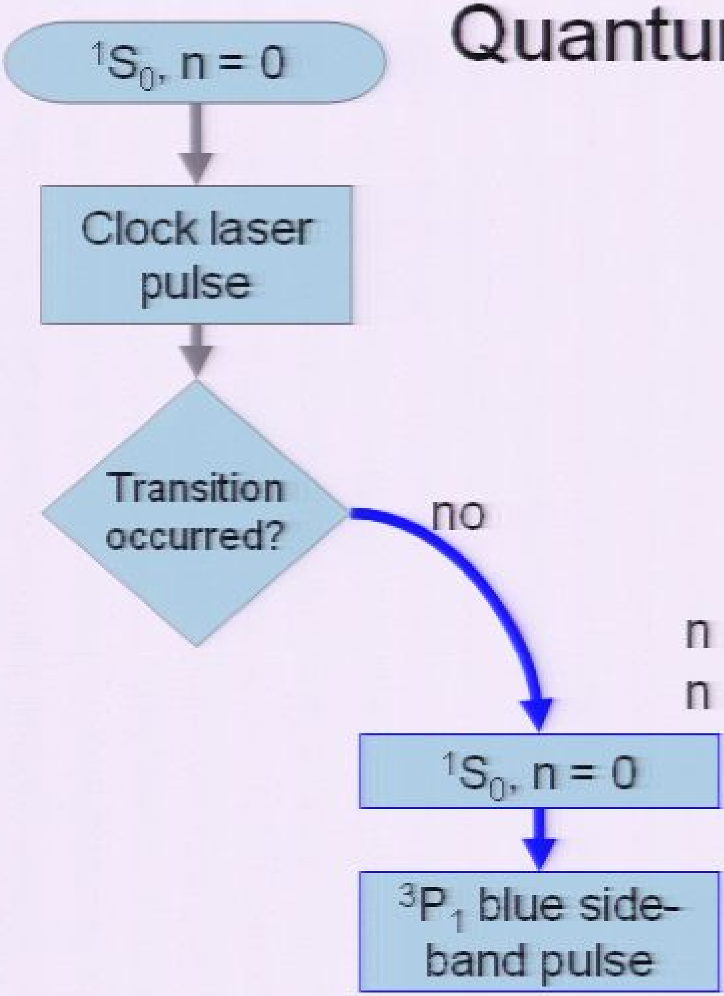

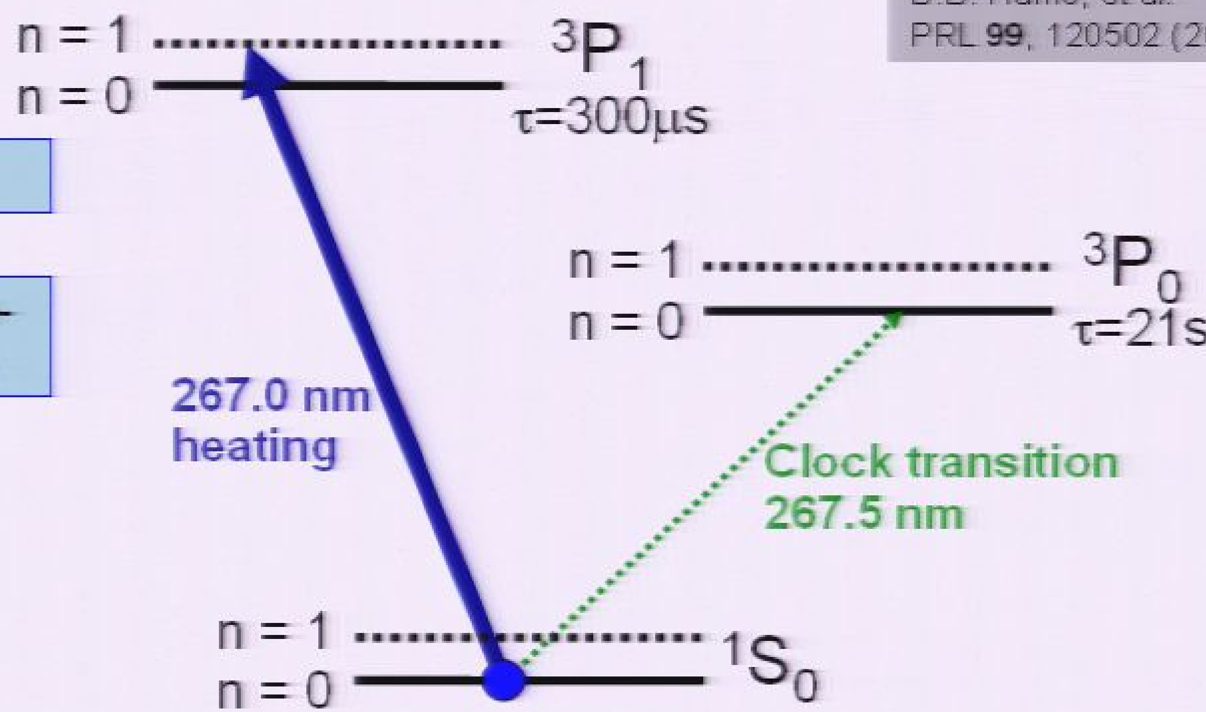

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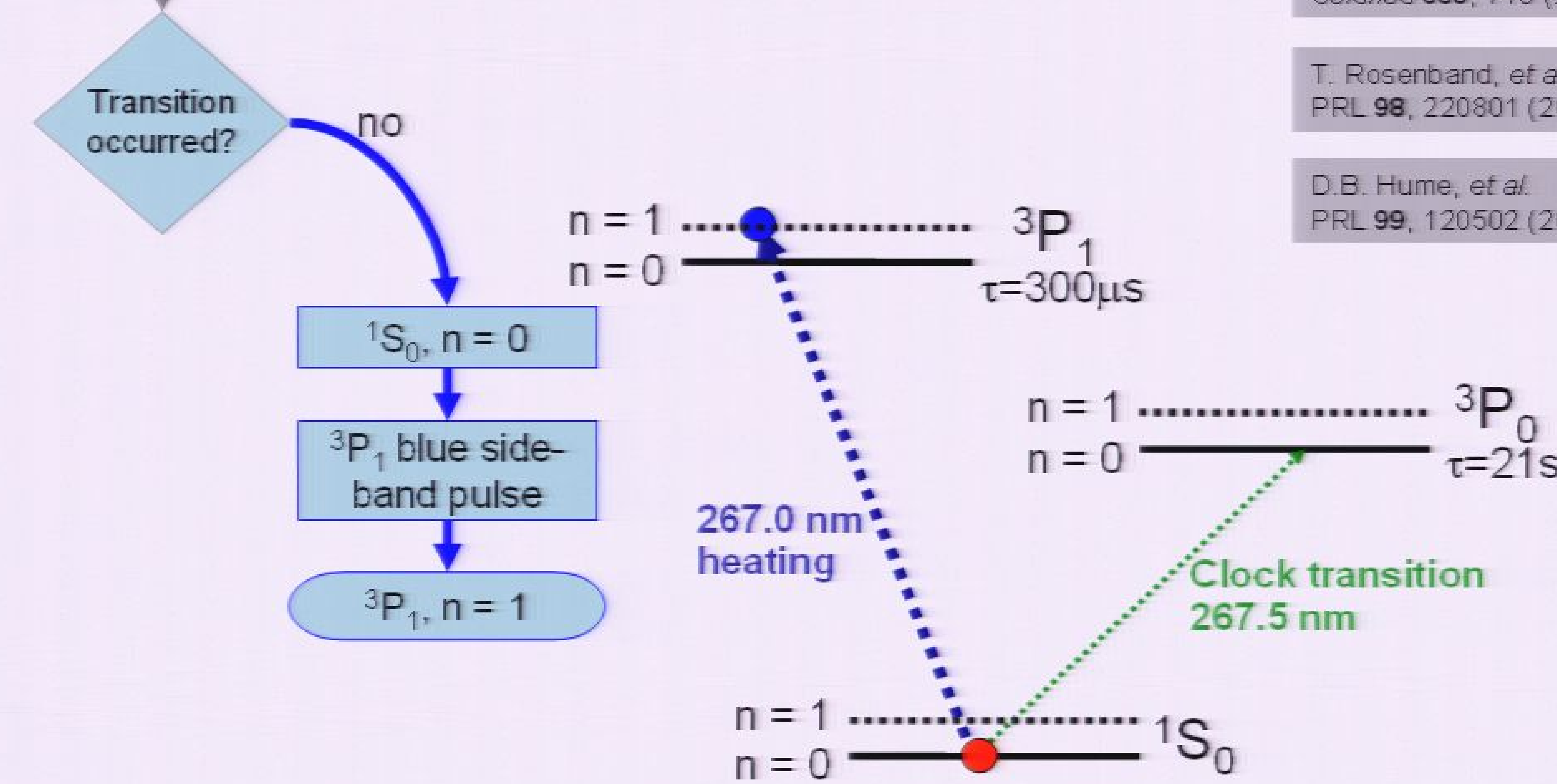

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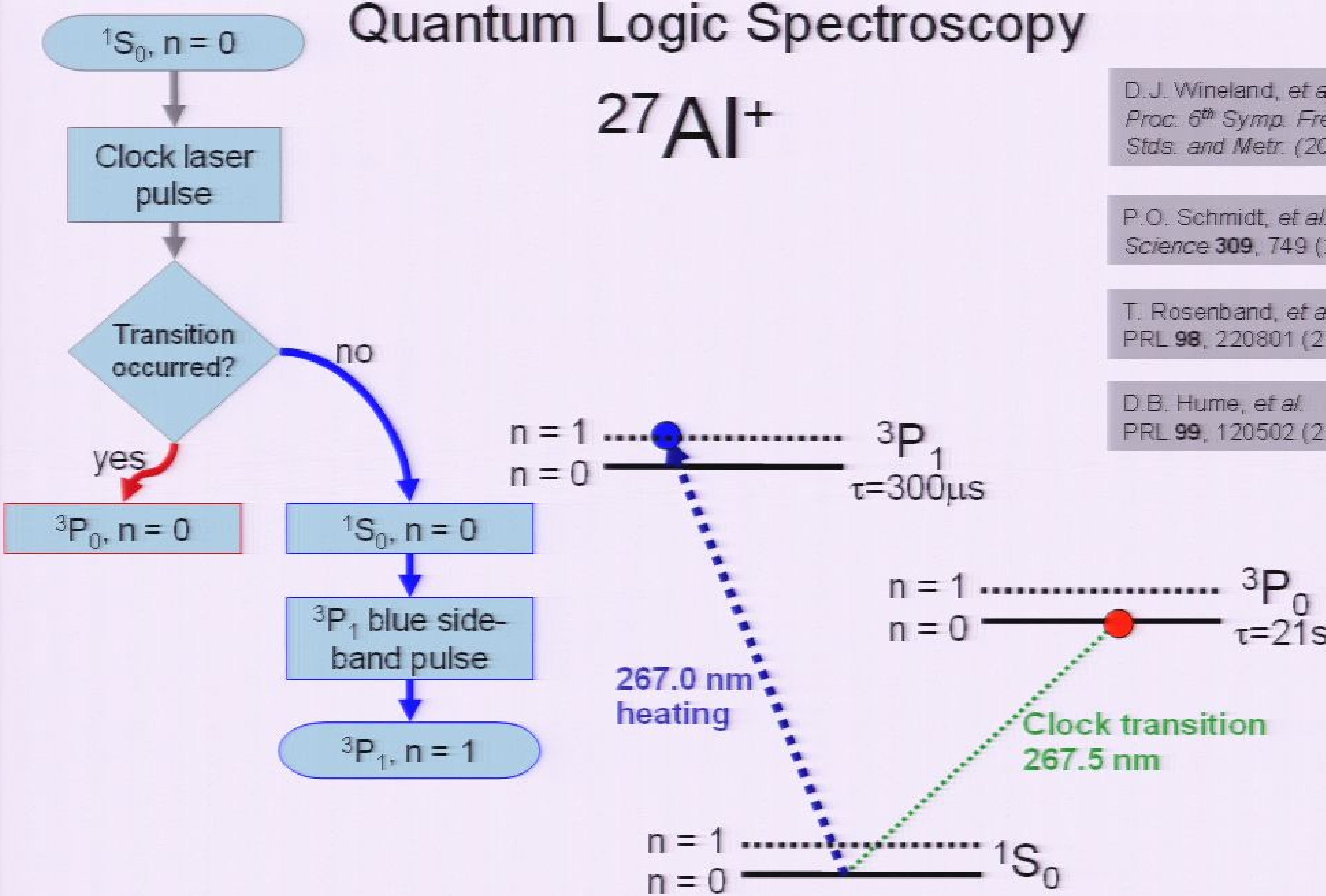

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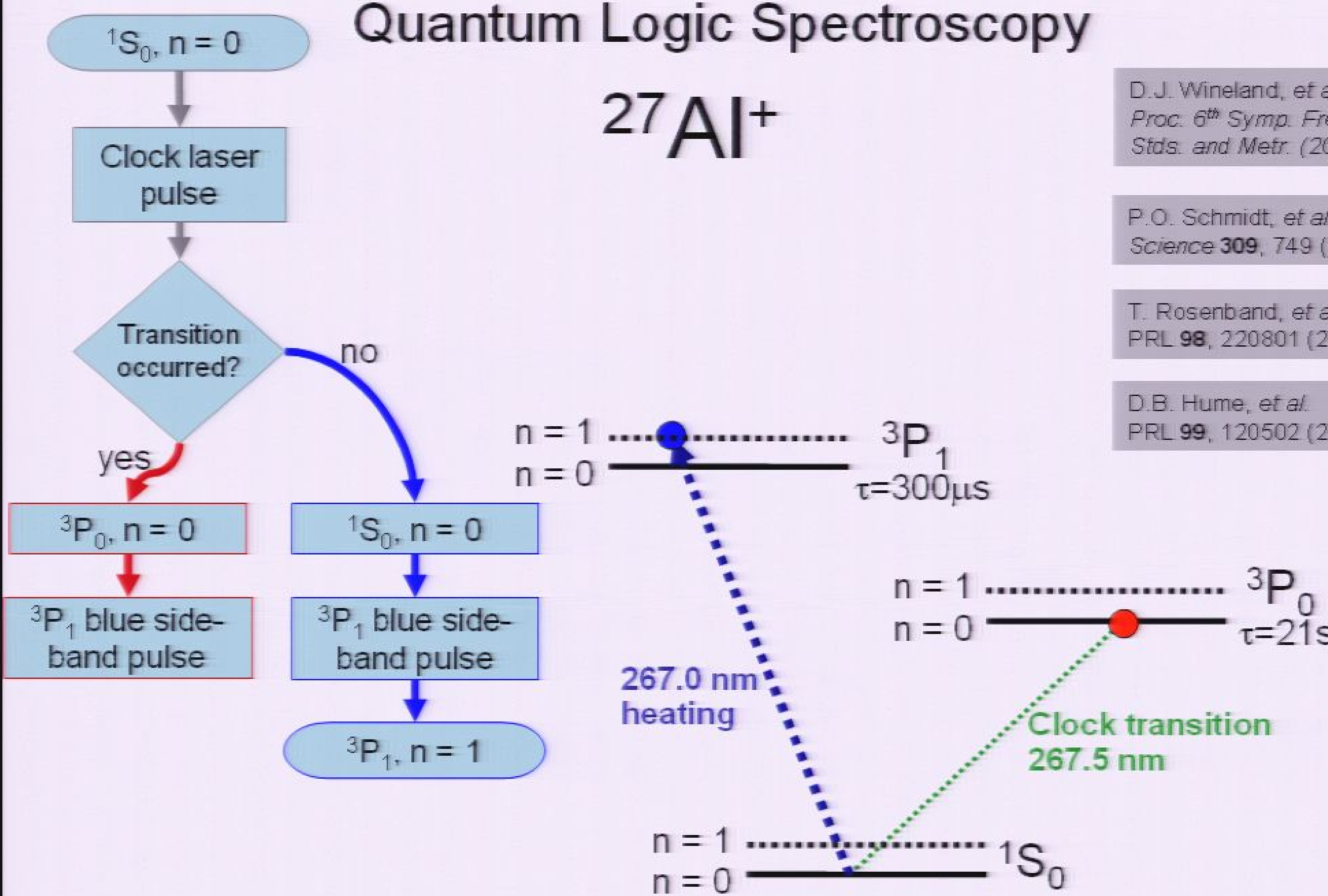

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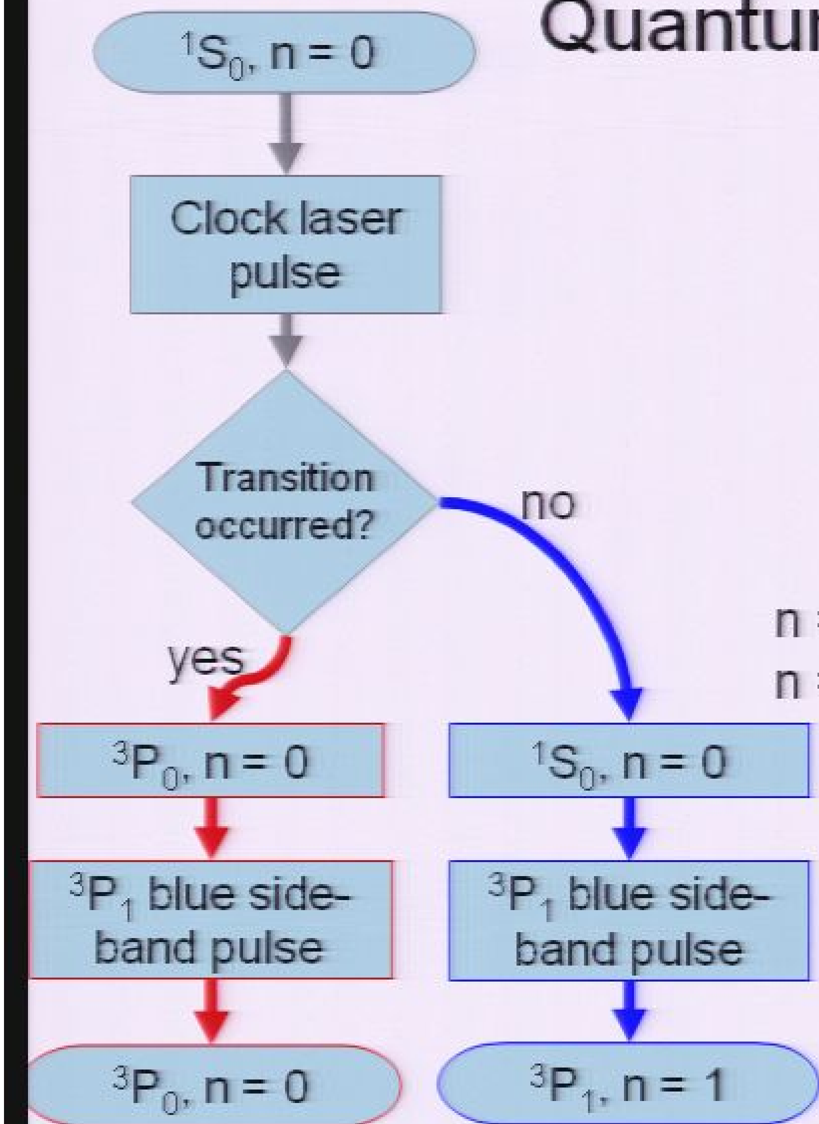

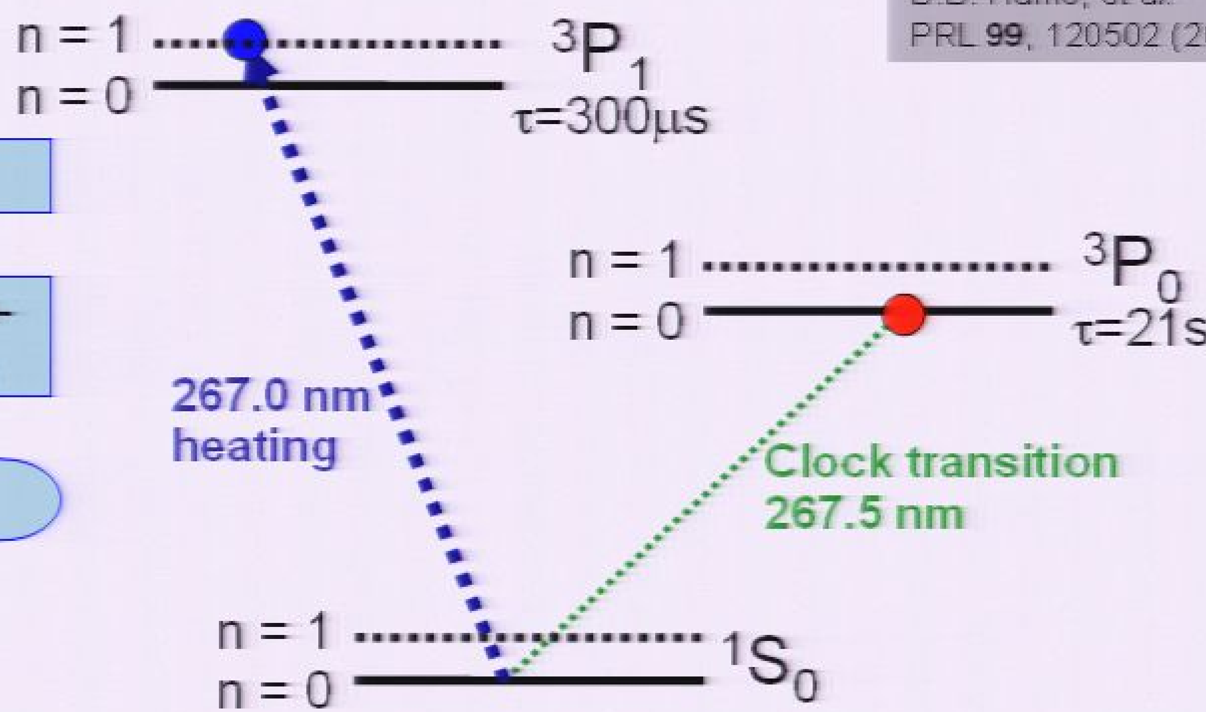

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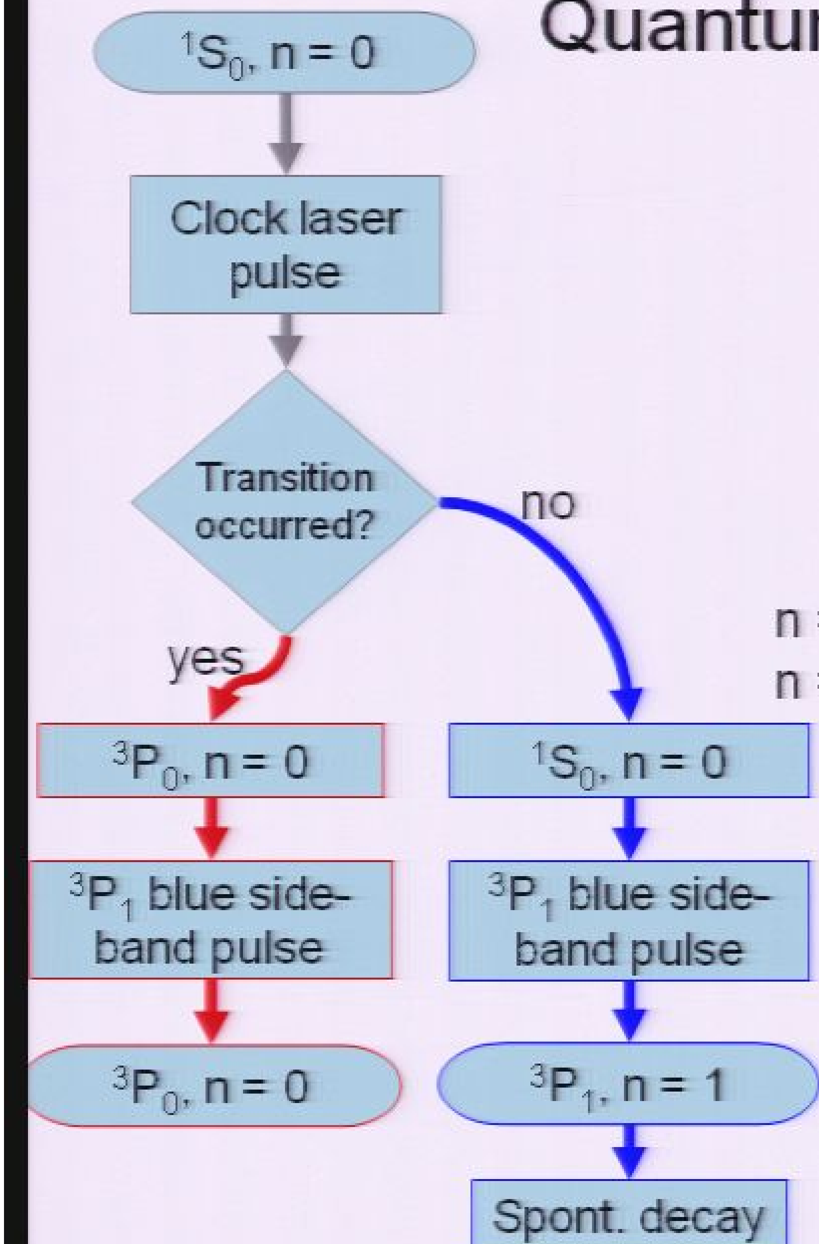

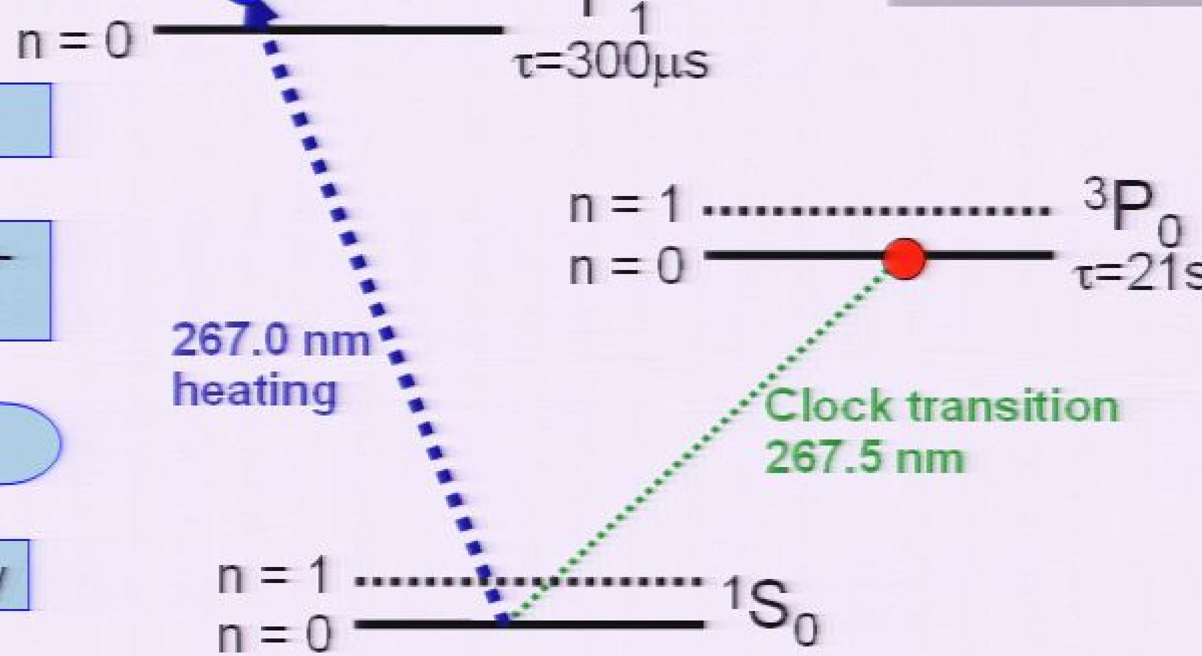

Quantum Logic Spectroscopy

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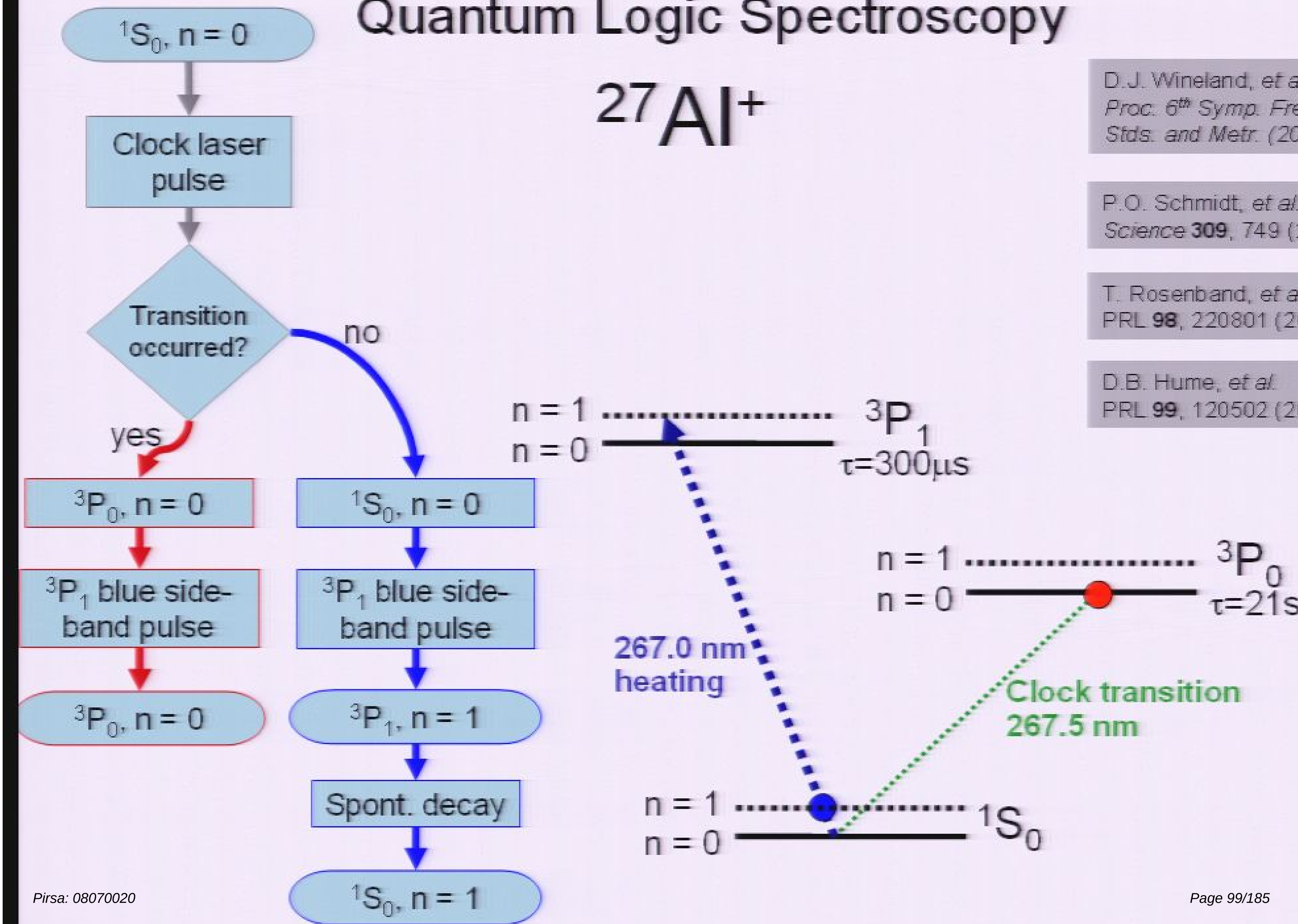
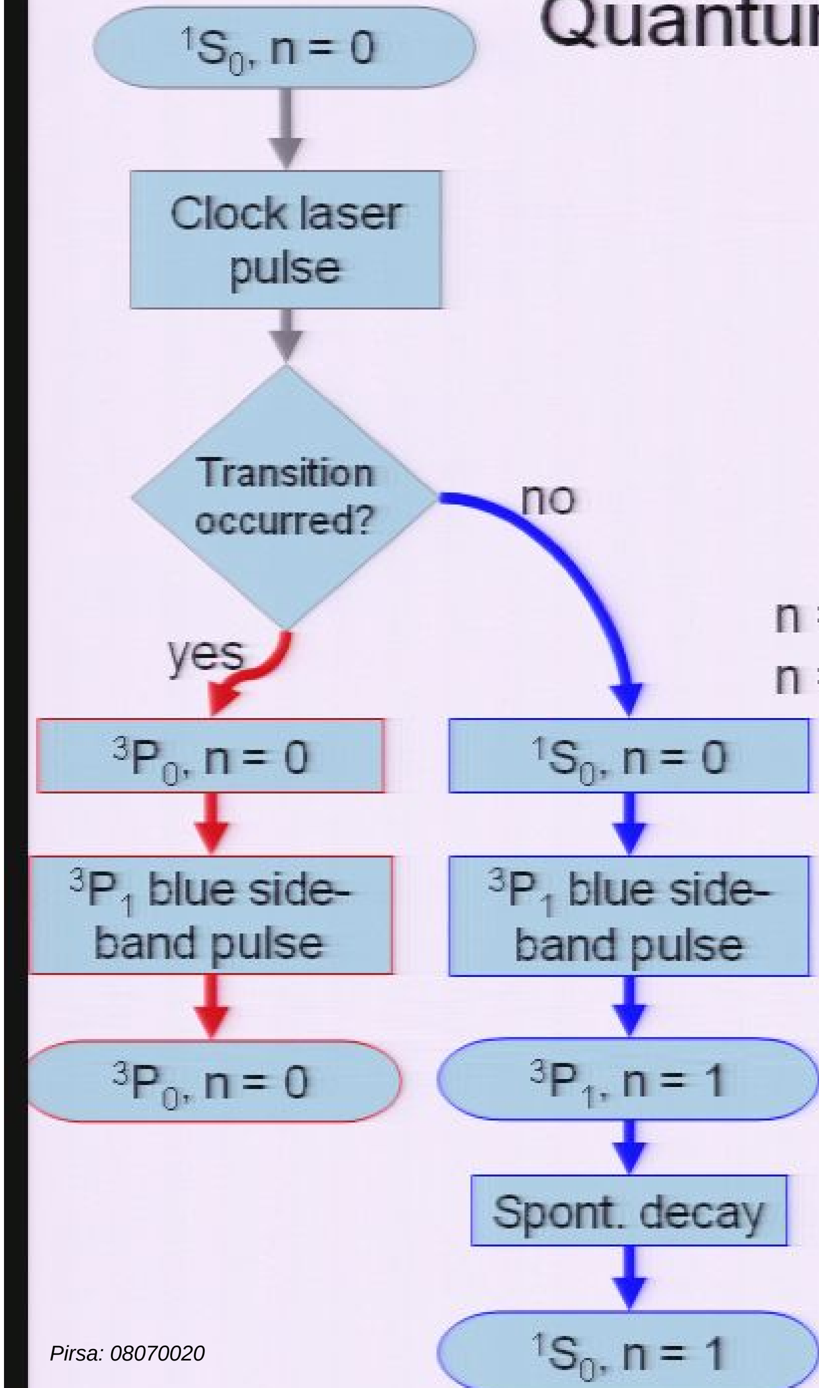


Quantum Logic Spectroscopy

$^{27}Al^+$



Quantum Non-Demolition (QND) Measurement of $^{27}Al^+$ state

D.J. Wineland, *et al.* *Proc. 6th Symp. Freq. Stds. and Metr. (2001)*

P.O. Schmidt, *et al.* *Science* **309**, 749 (2005)

T. Rosenband, *et al.* PRL **98**, 220801 (2007)

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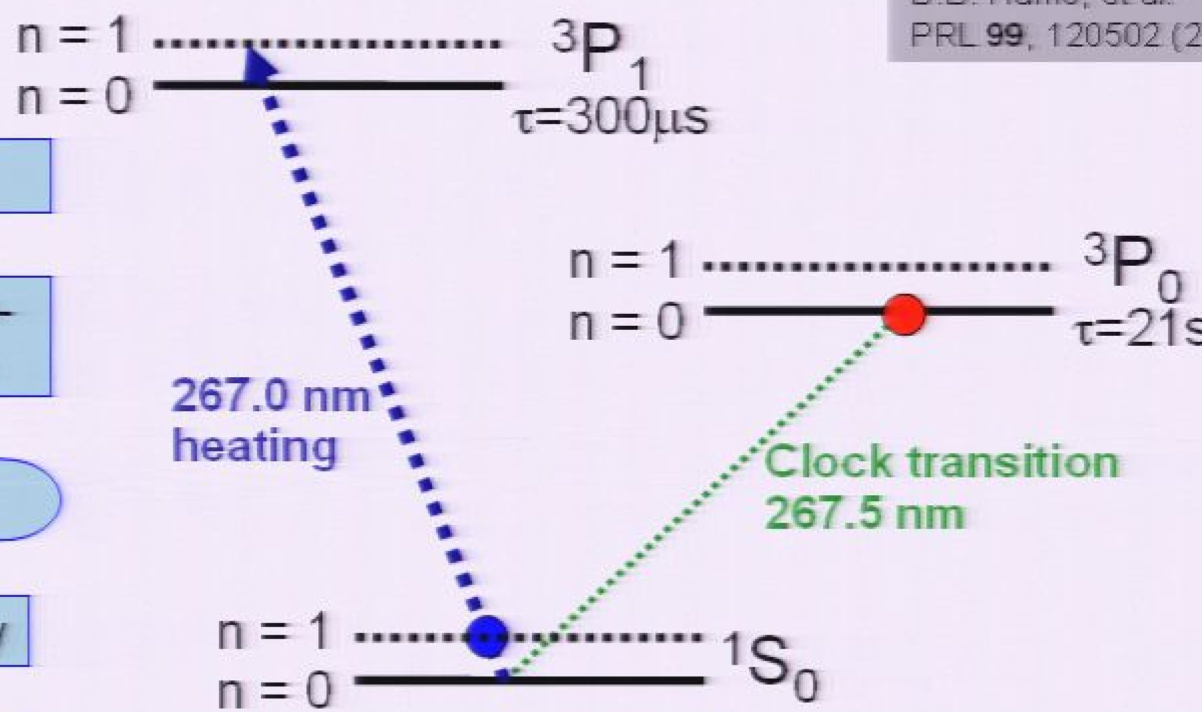
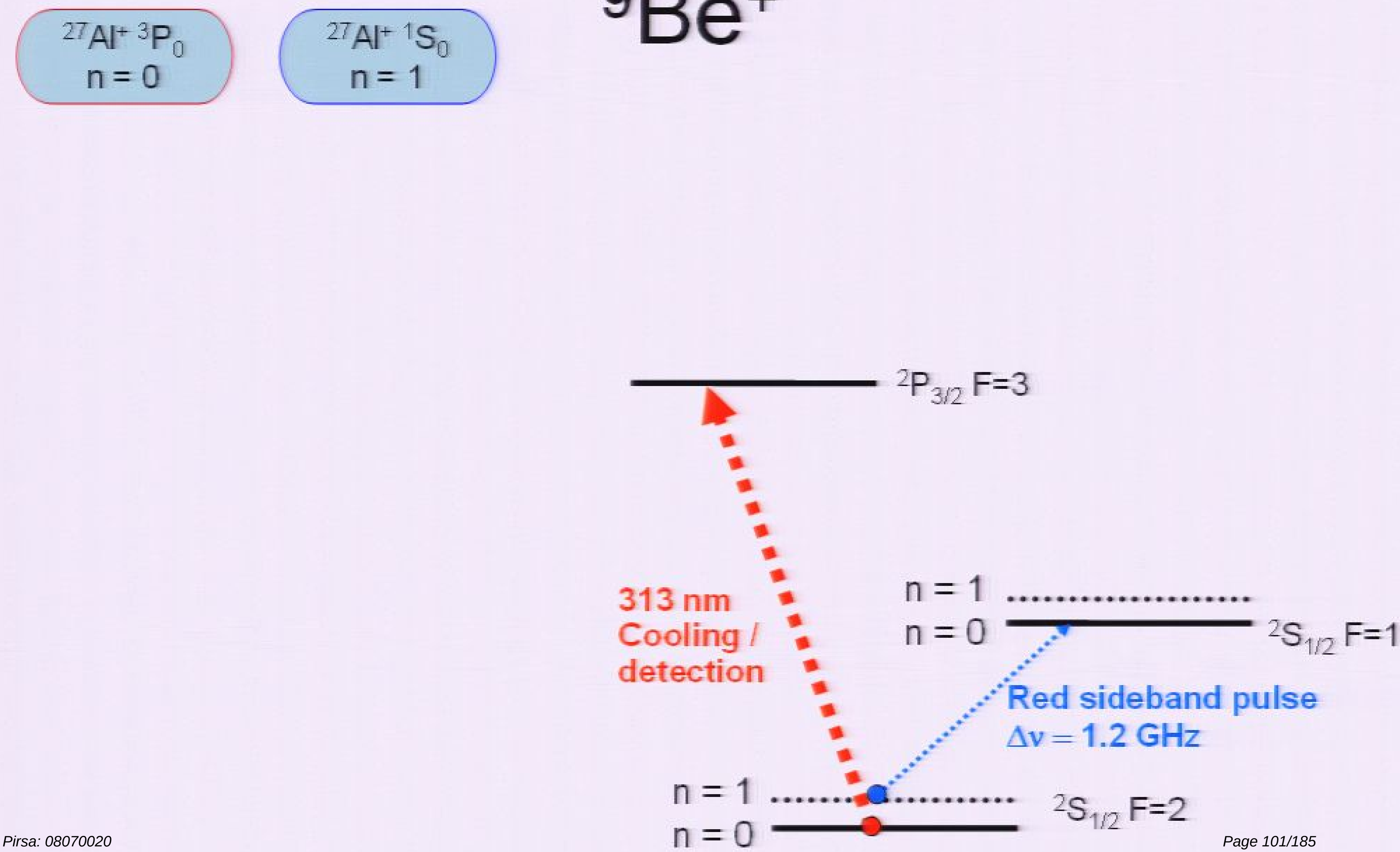
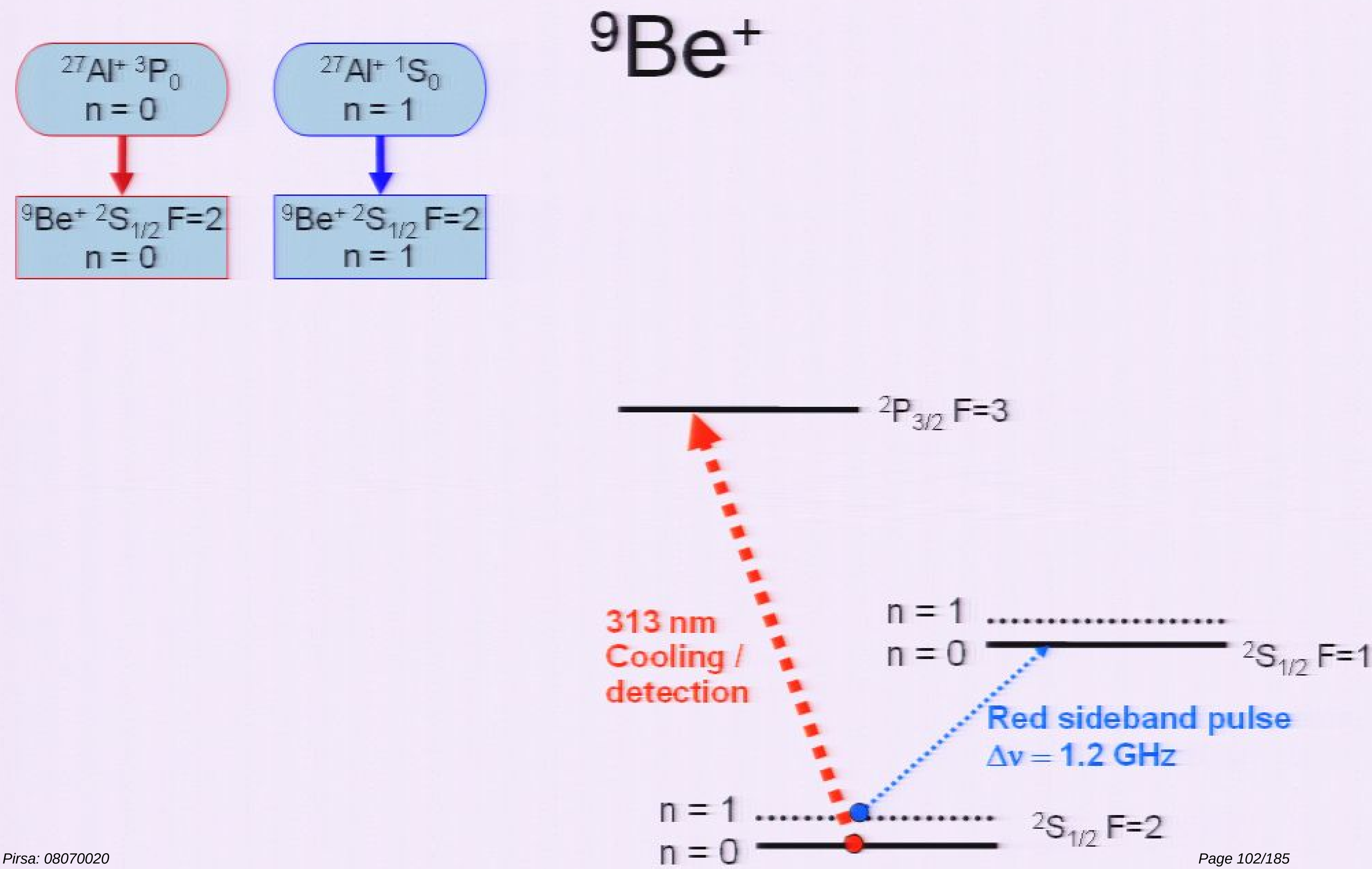


Single phonon detection

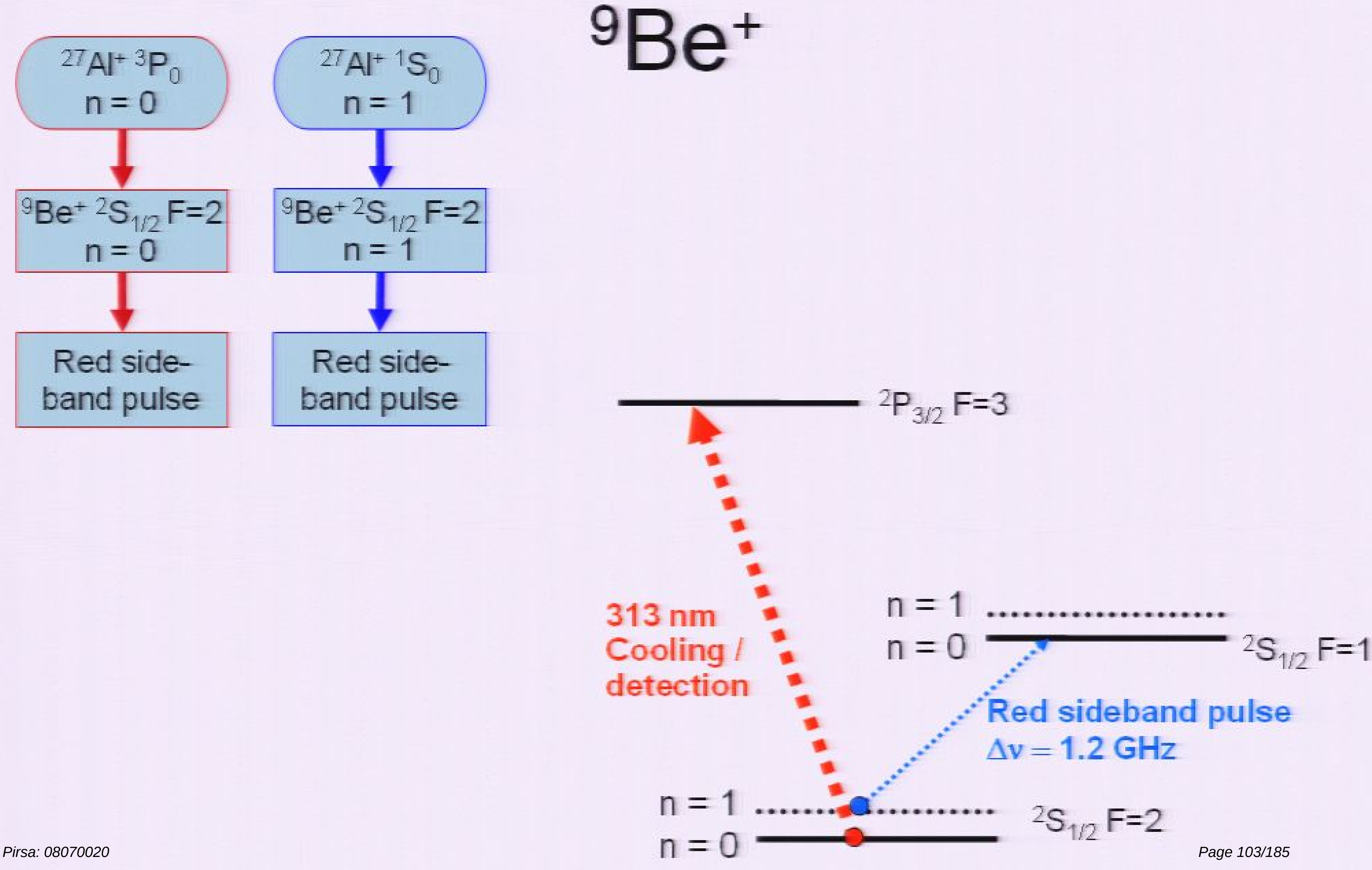
$^{9}Be^{+}$



Single phonon detection

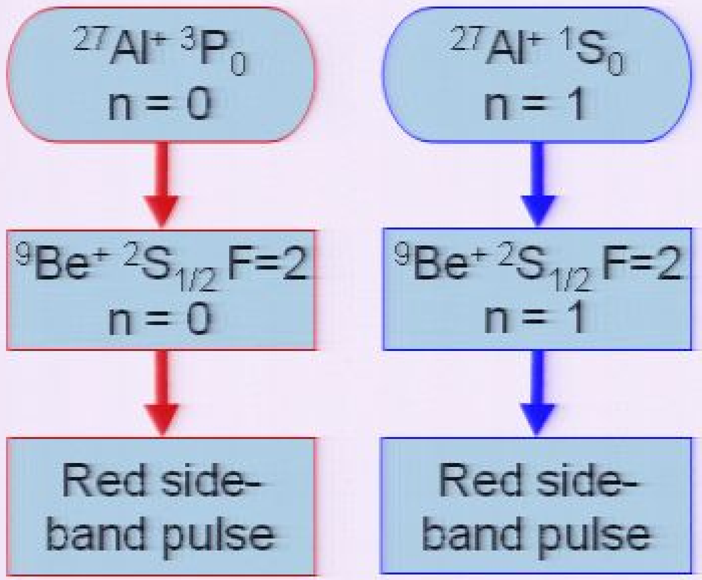


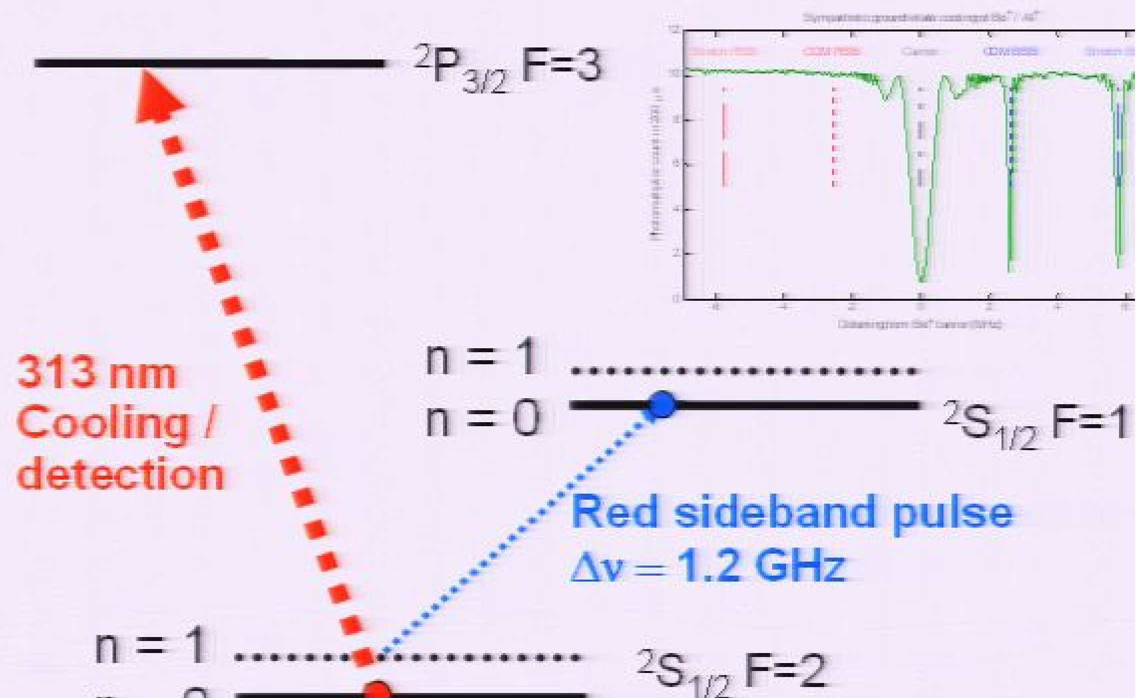
Single phonon detection



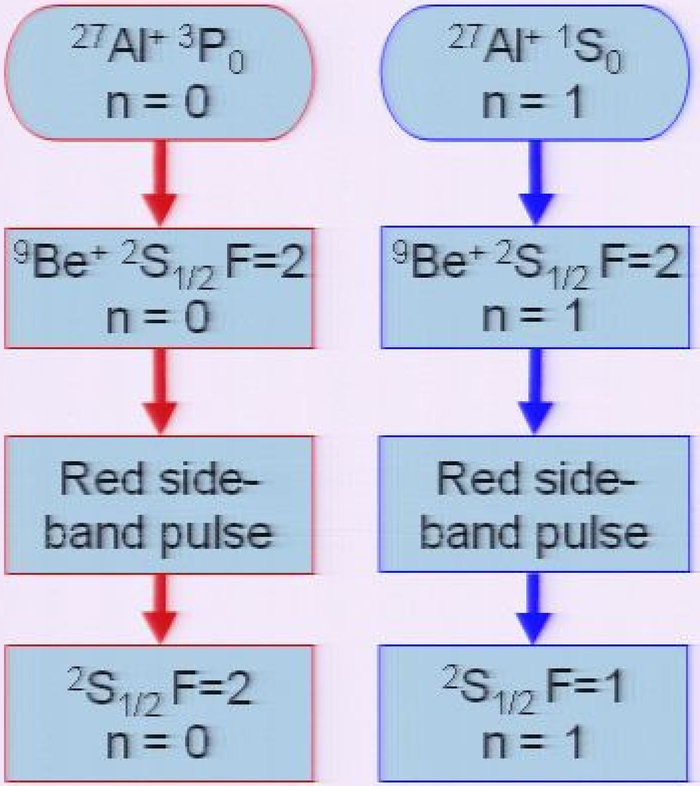
Single phonon detection

$^9Be^+$

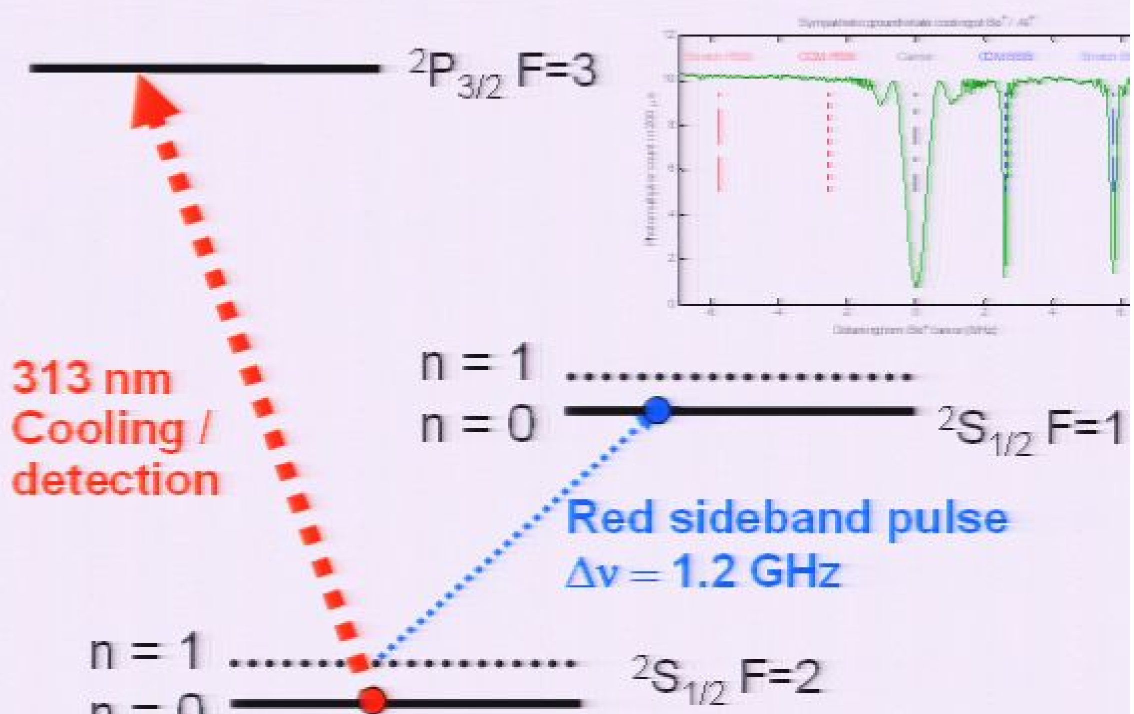




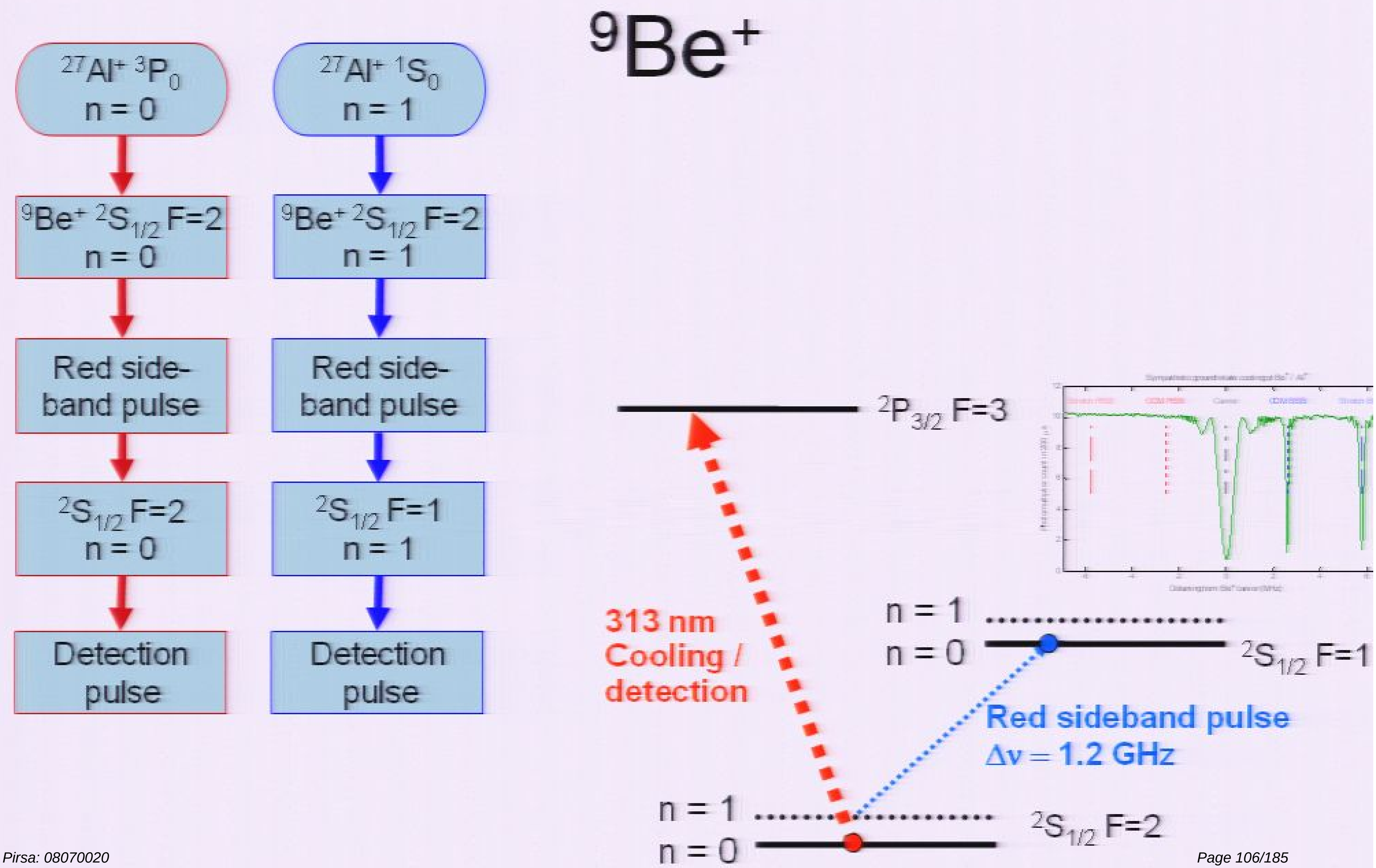
Single phonon detection



$^9Be^+$



Single phonon detection



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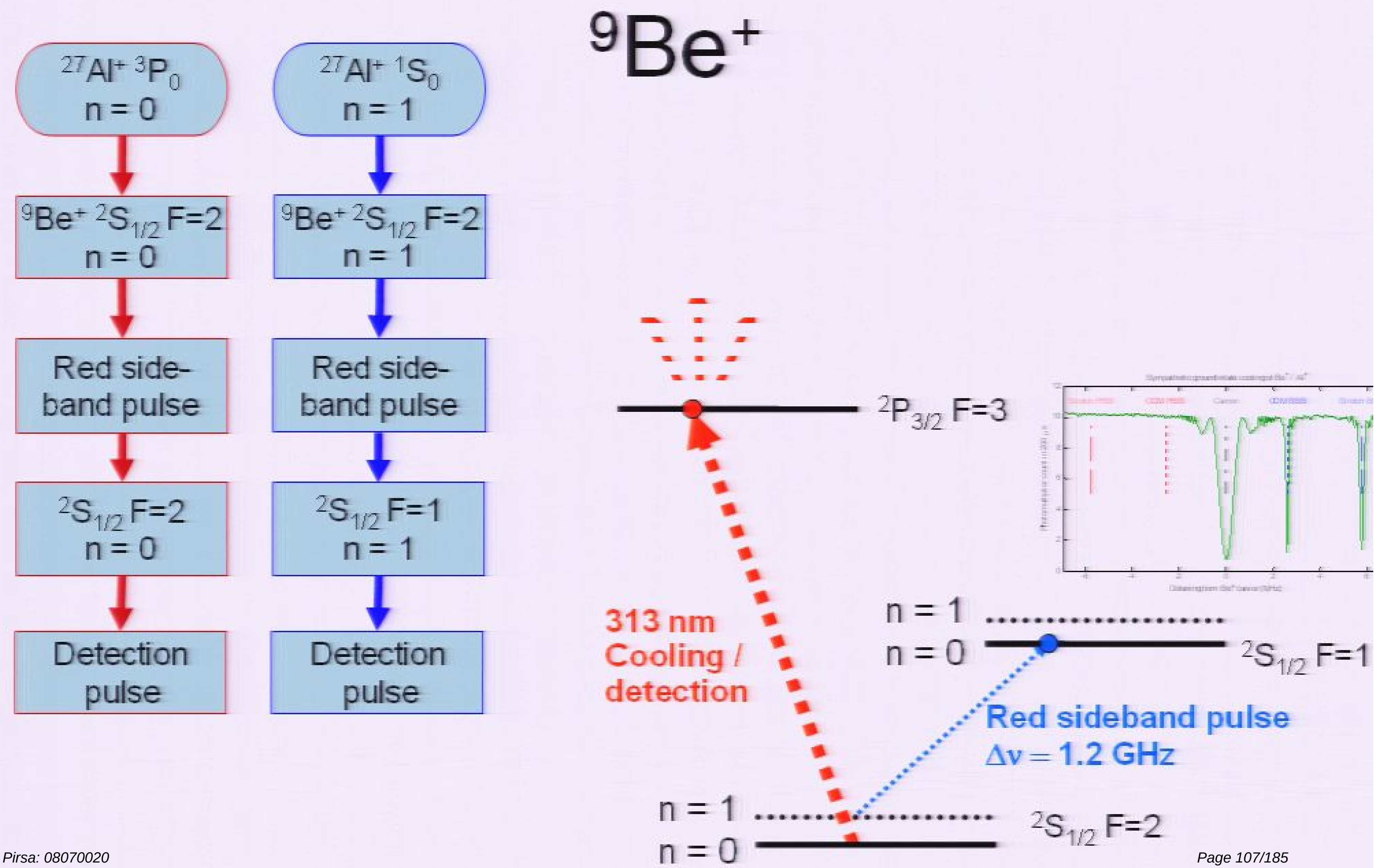
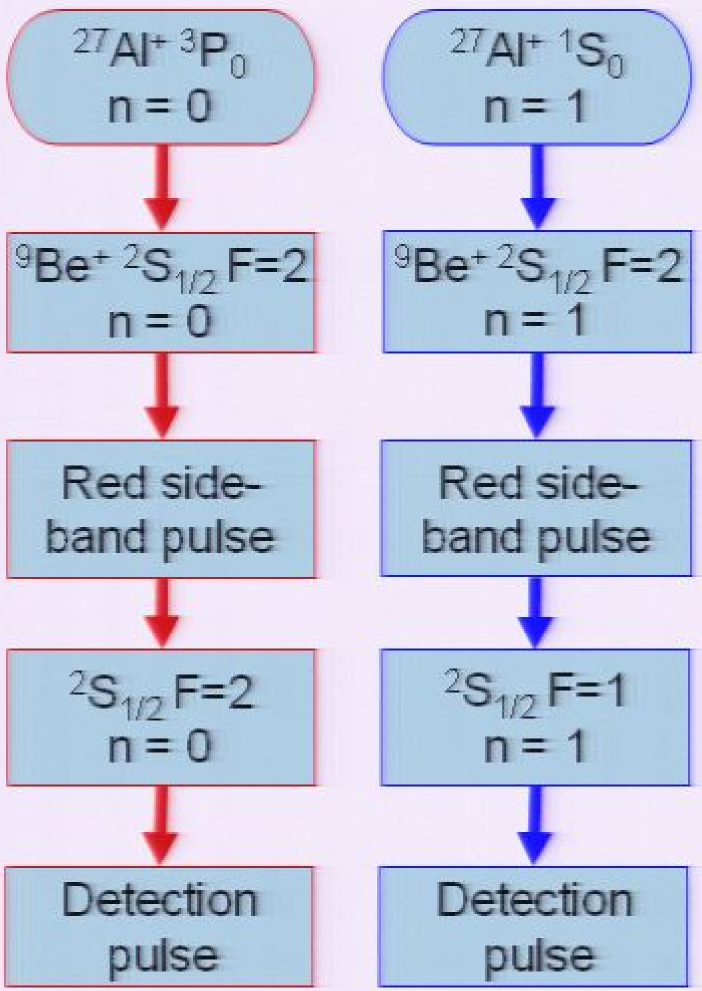
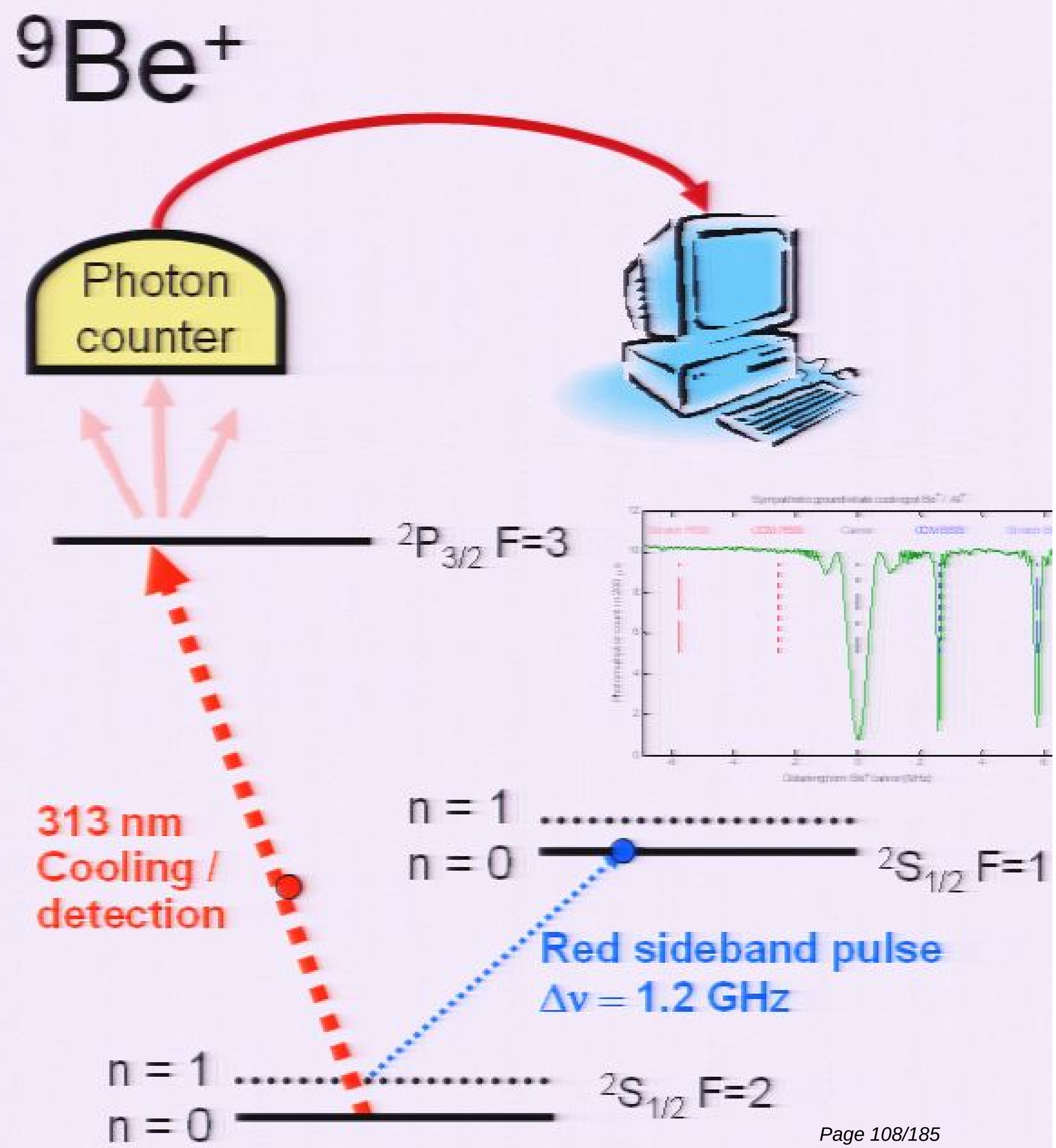
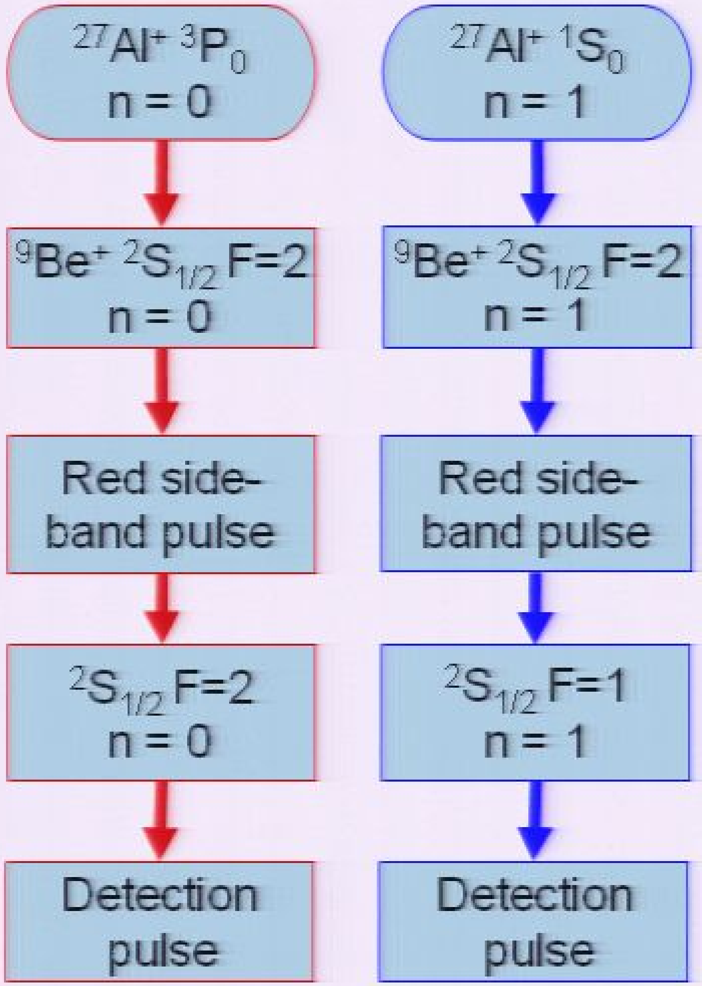


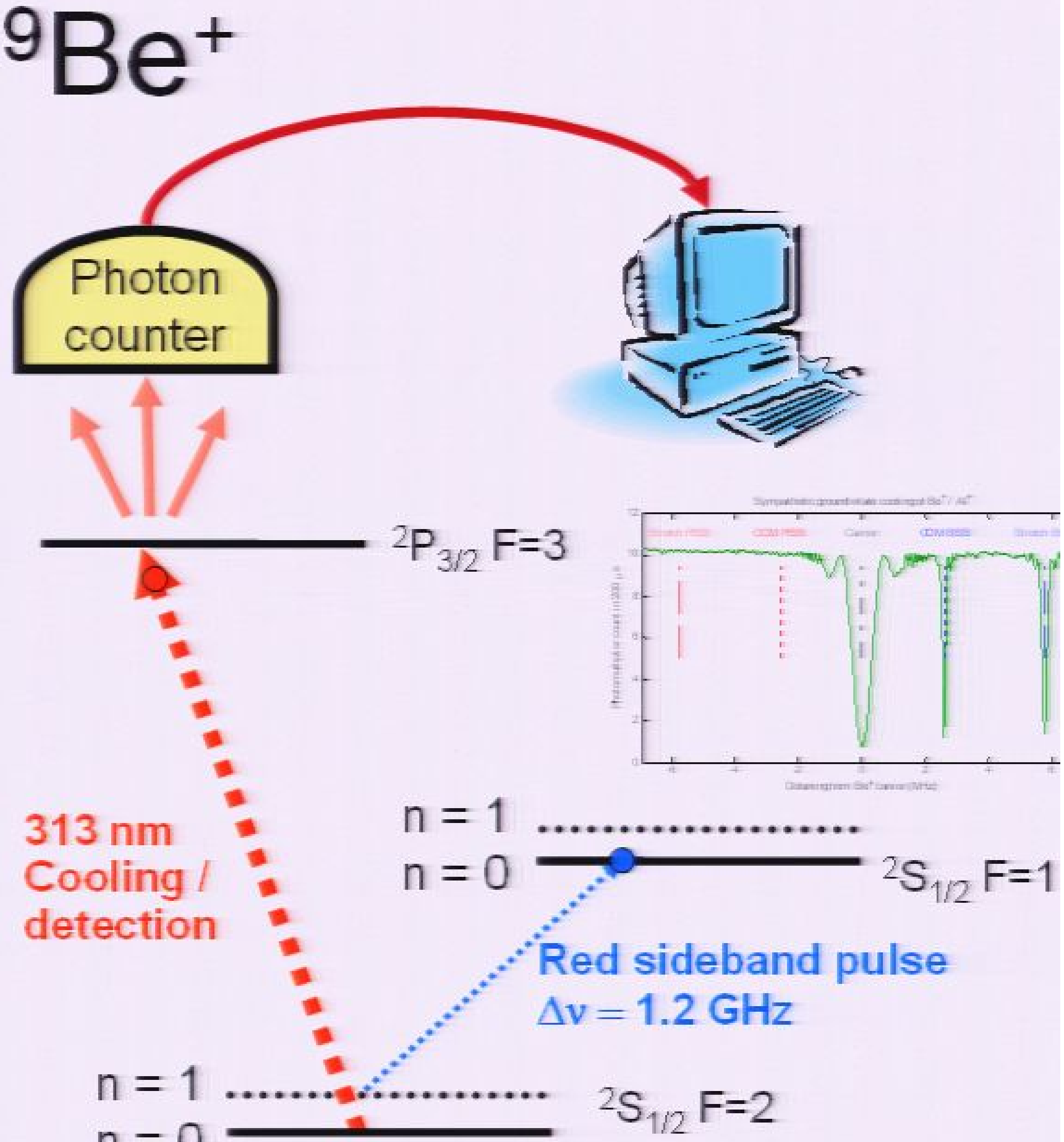
Single phonon detection



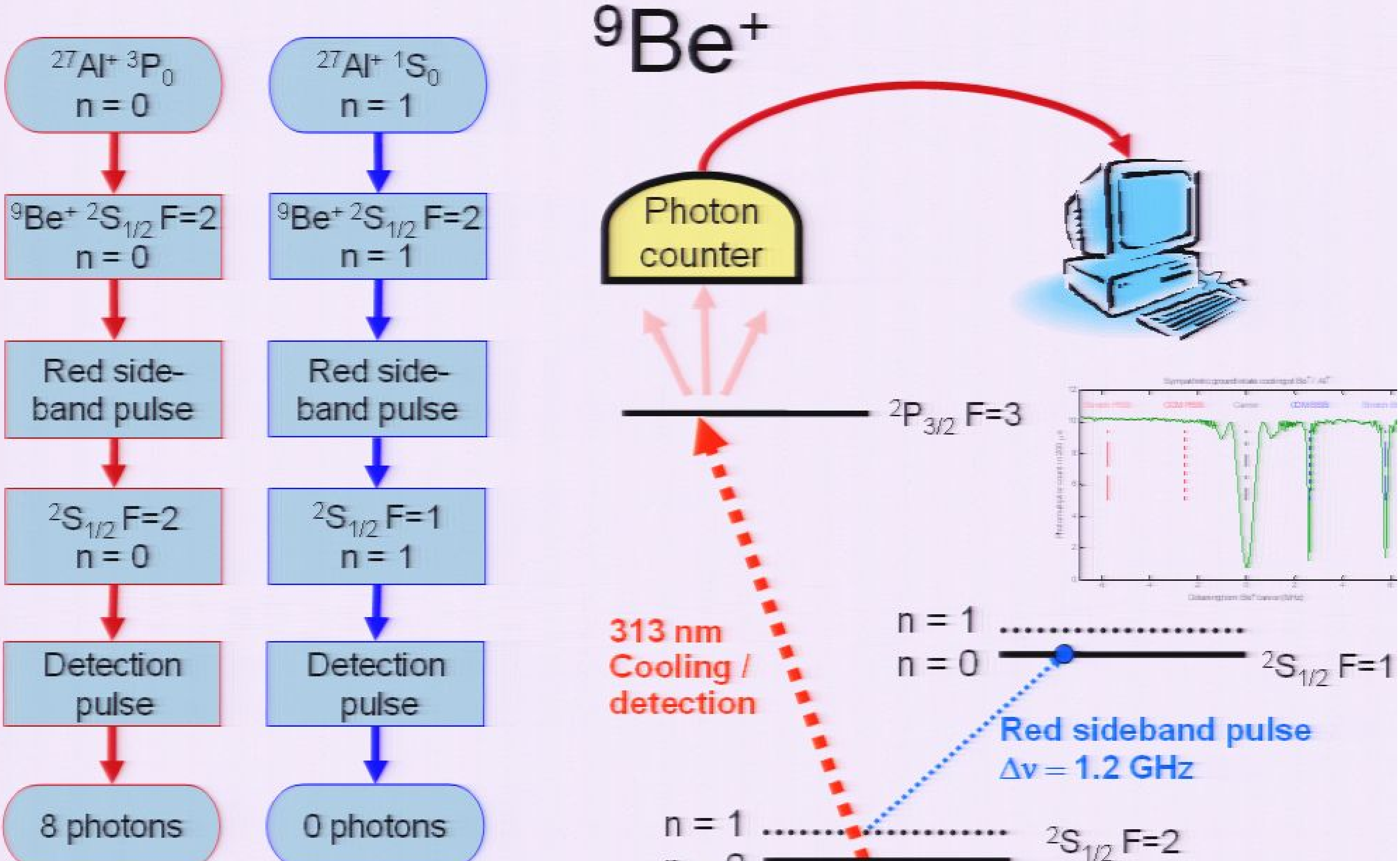


Single phonon detection

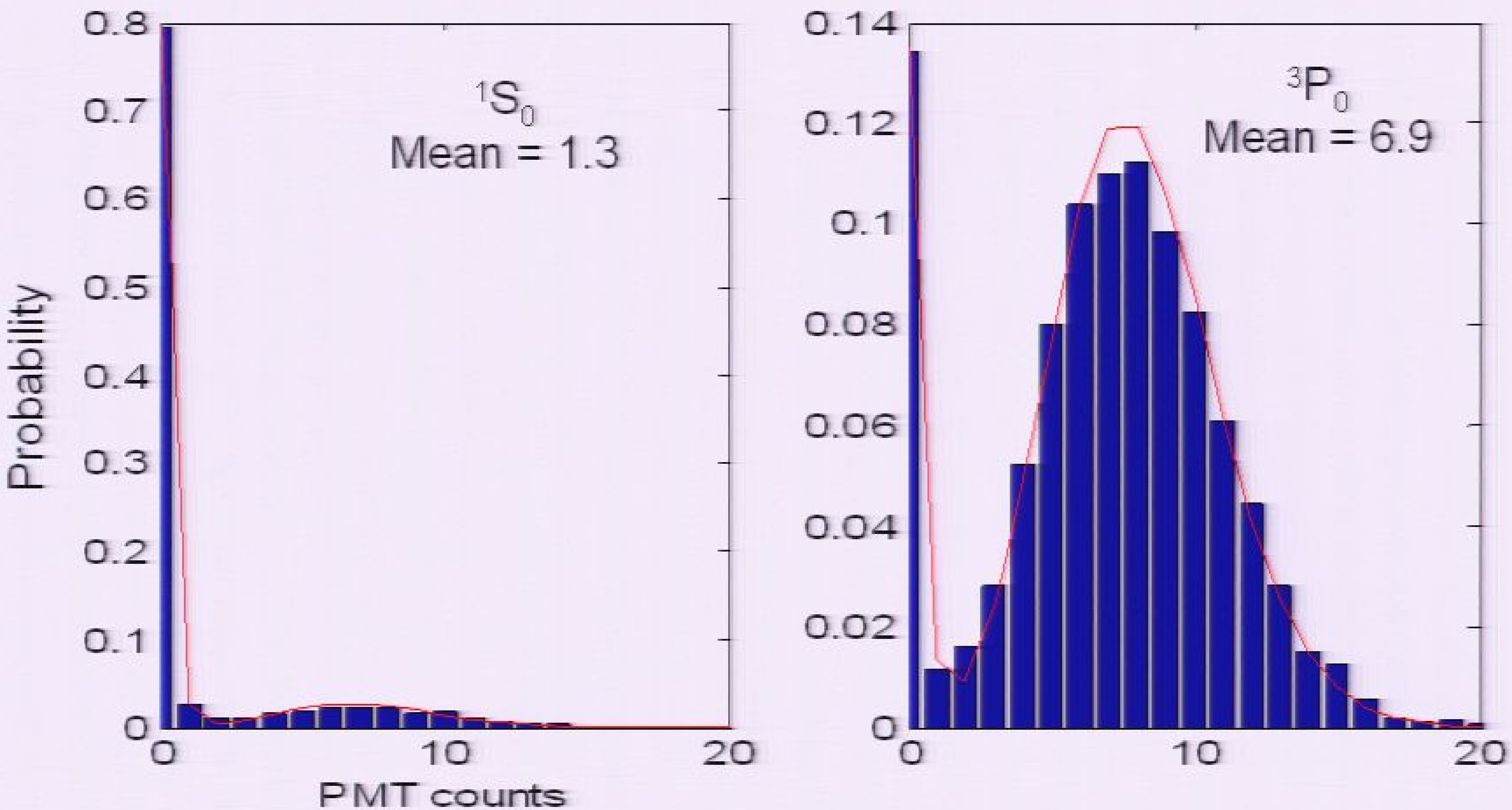




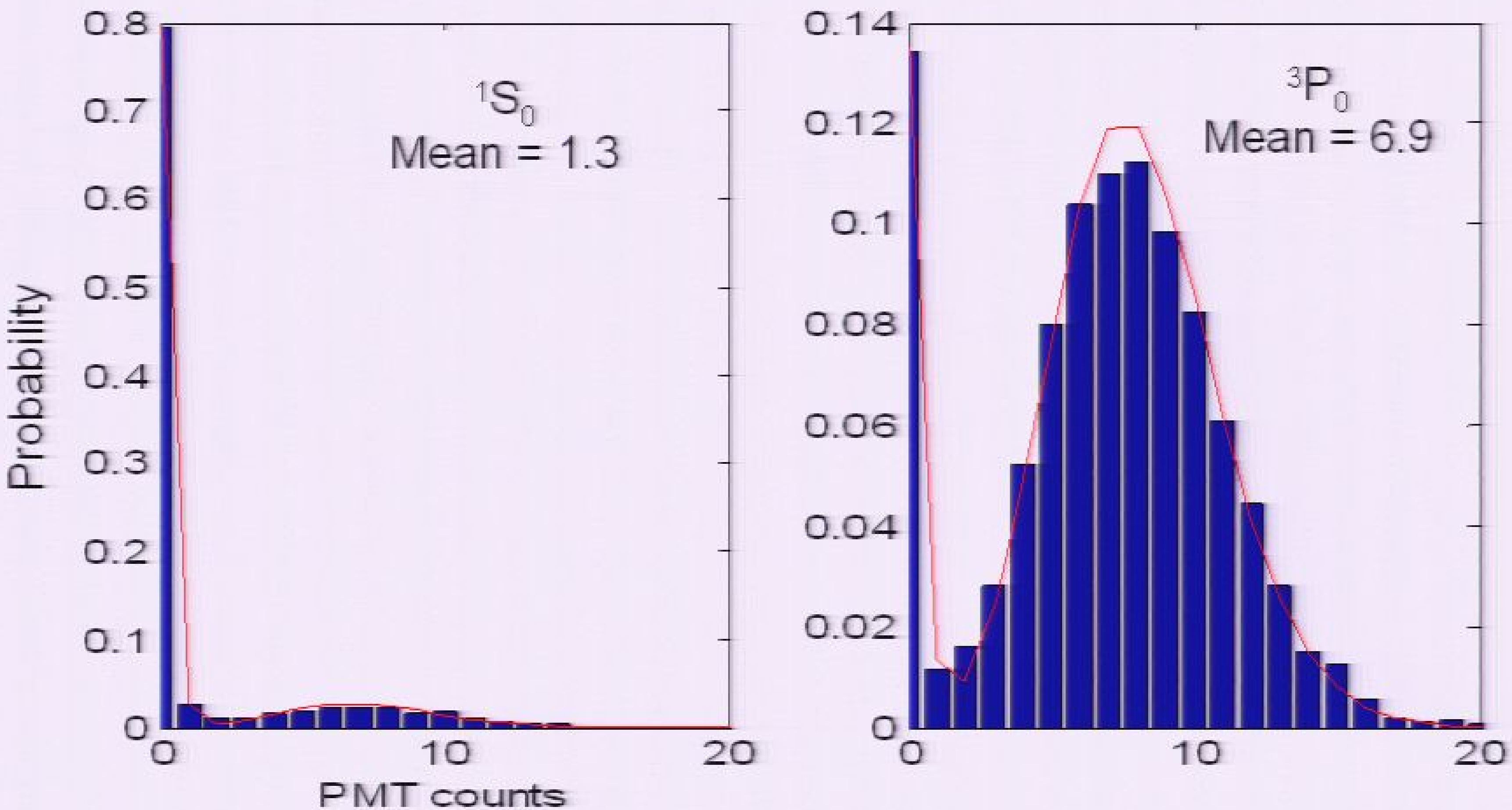
Single phonon detection



Detection outcomes

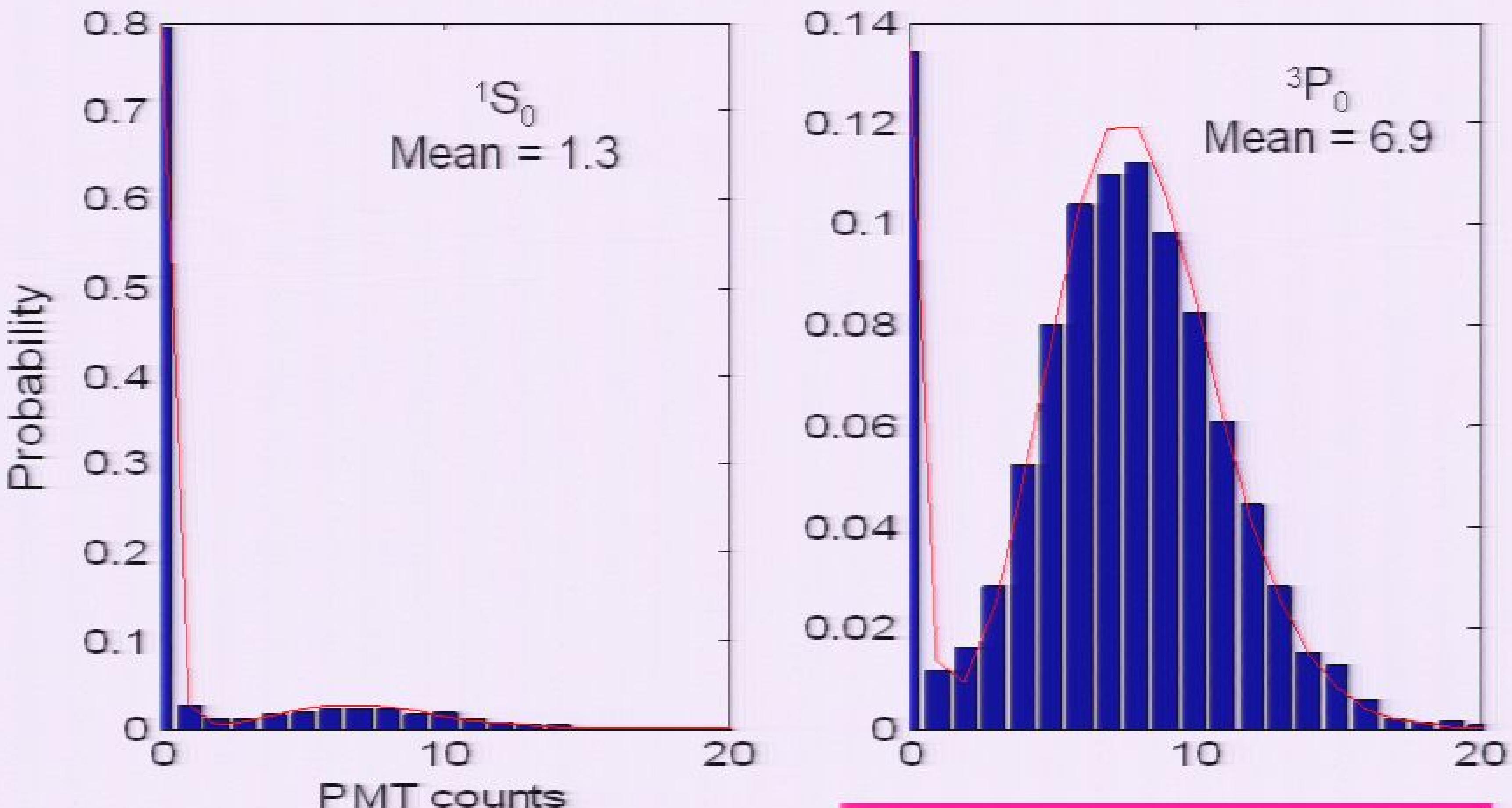


Detection outcomes



Adaptive Bayesian detection

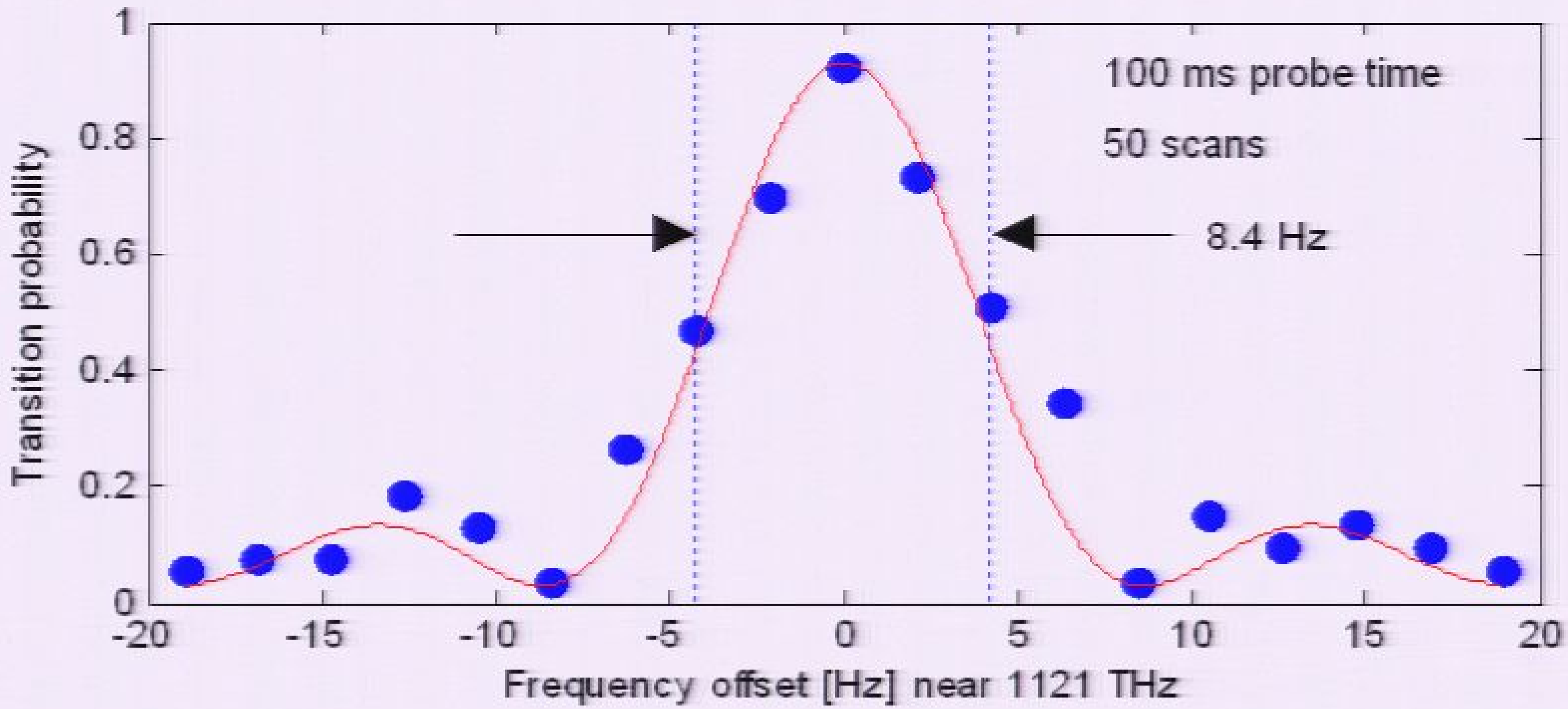
Detection outcomes

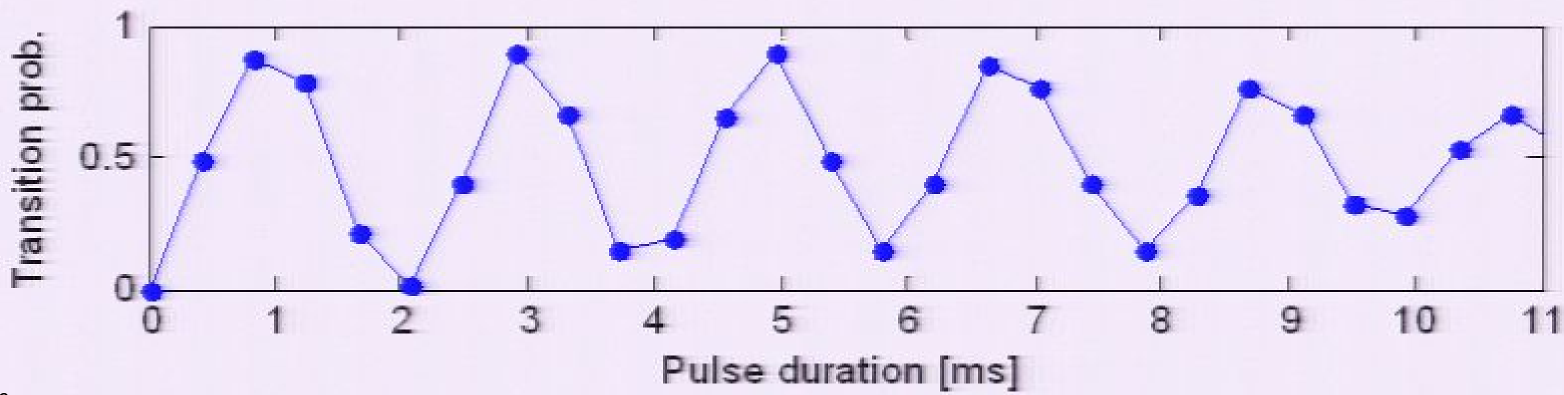


99.94% Detection fidelity

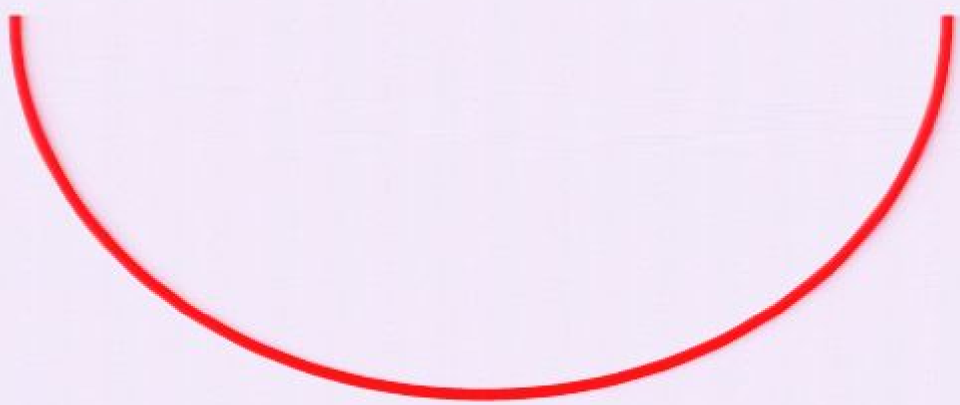
Adaptive Bayesian detection

Rabi Spectroscopy





Using two ions



Using two ions

Clock ion (Al^{+}) for very accurate spectroscopy

Using two ions

Clock ion (Al^+) for very accurate spectroscopy

Using two ions

Clock ion (Al^+) for very accurate spectroscopy
Logic ion (Be^+) for cooling and readout

Using two ions

Clock ion (Al^+) for very accurate spectroscopy

Logic ion (Be^+) for cooling and readout

Using two ions

Clock ion (Al^+) for very accurate spectroscopy

Logic ion (Be^+) for cooling and readout

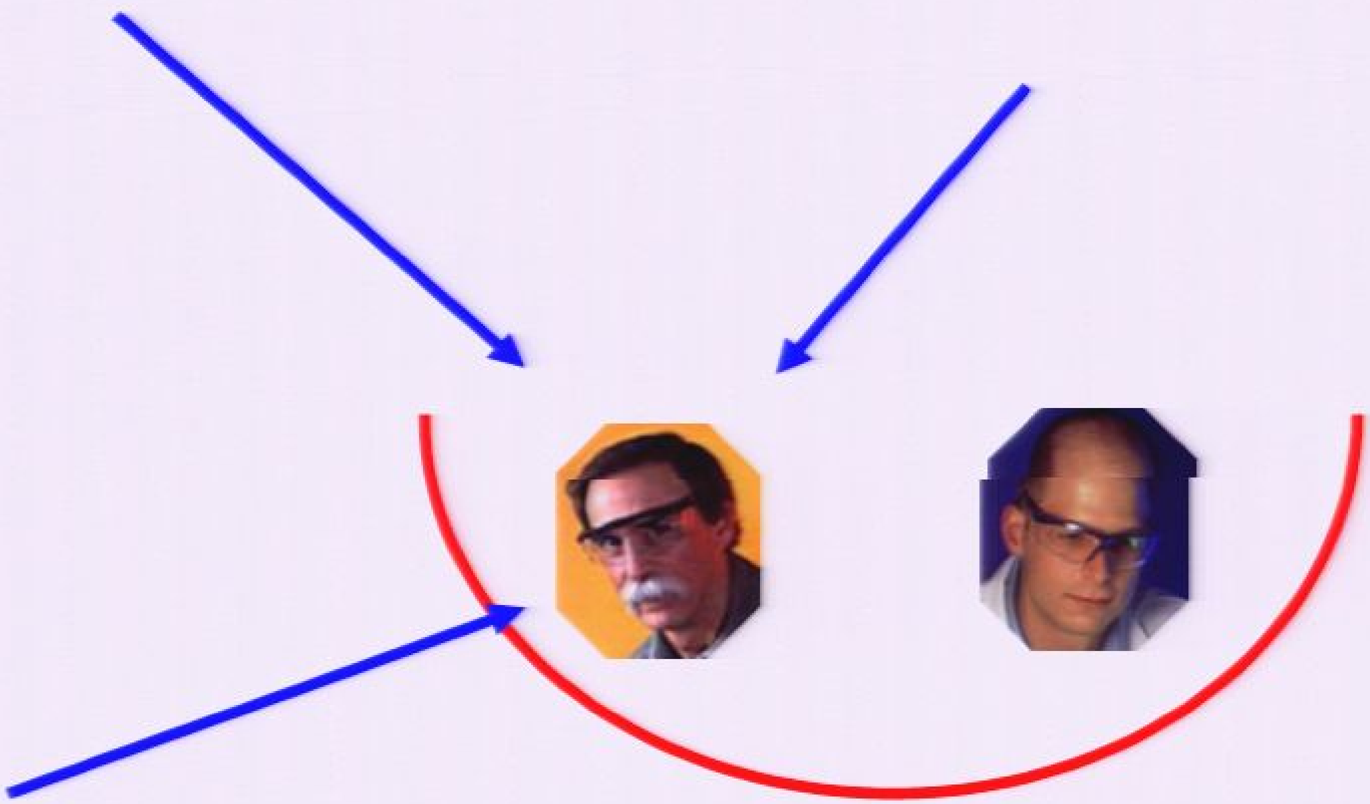
Coulomb-force couples the motion of the ions

Using two ions

Clock ion (Al^+) for very accurate spectroscopy
Logic ion (Be^+) for cooling and readout
Coulomb-force couples the motion of the ions

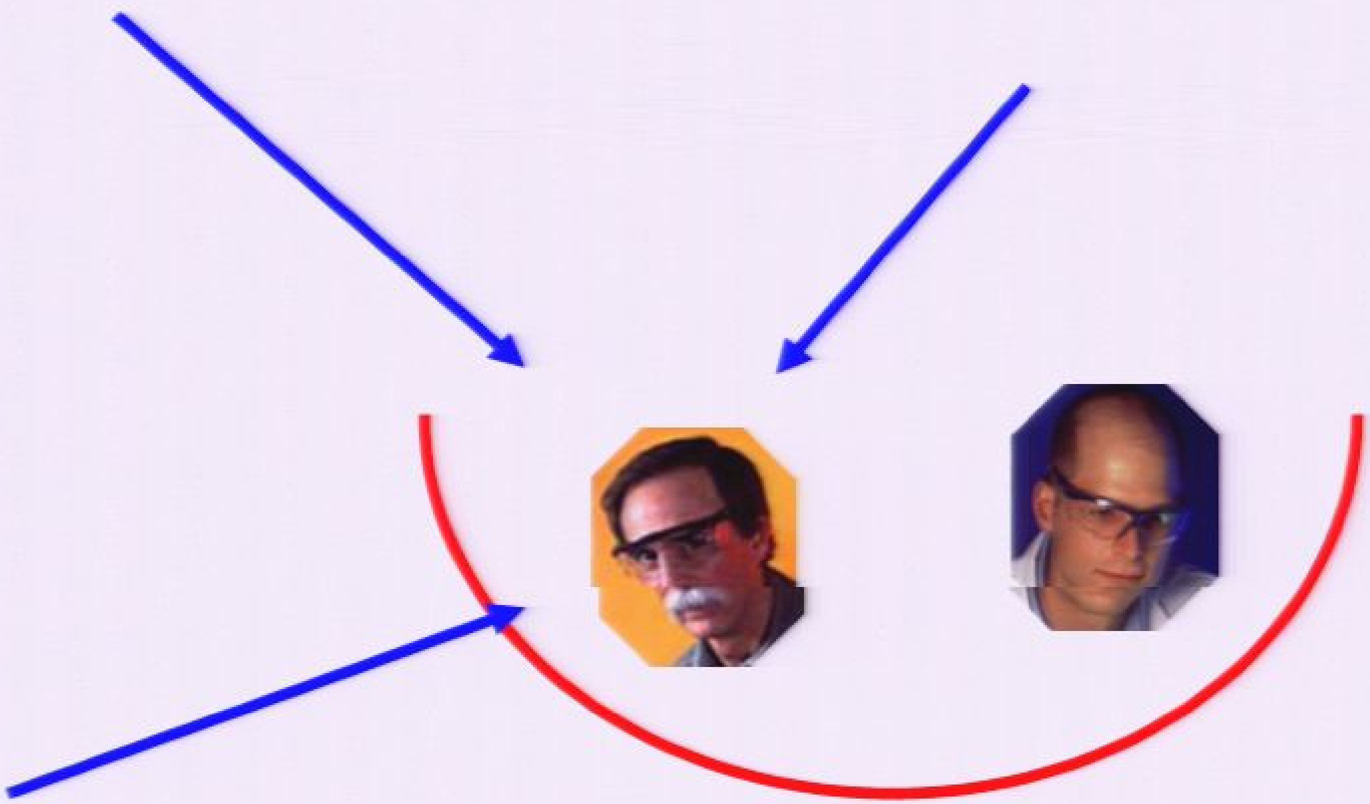
Using two ions

Clock ion (Al^+) for very accurate spectroscopy
Logic ion (Be^+) for cooling and readout
Coulomb-force couples the motion of the ions
⇒ Cooling Be+ leads to cooling of Al+



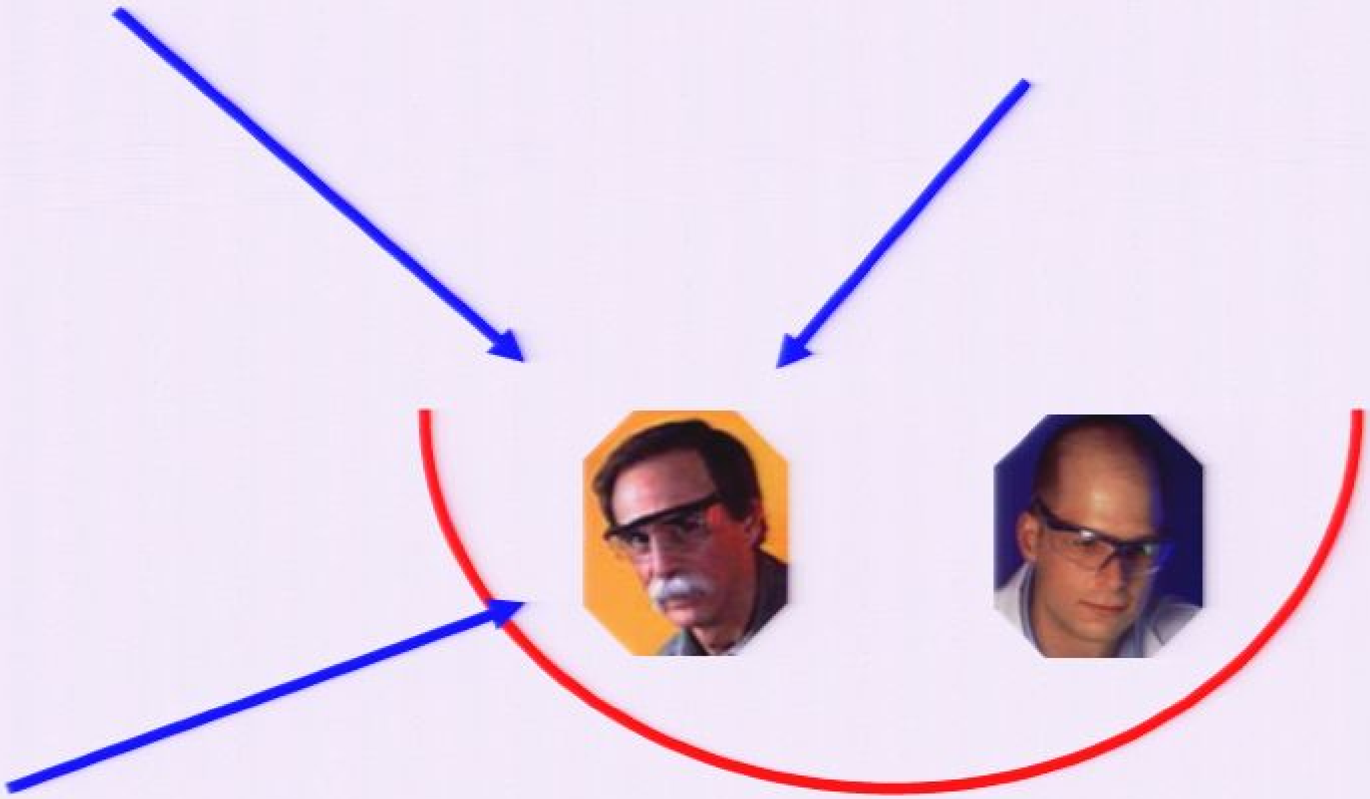
Using two ions

Clock ion (Al^+) for very accurate spectroscopy
Logic ion (Be^+) for cooling and readout
Coulomb-force couples the motion of the ions
$\Rightarrow$ Cooling Be+ leads to cooling of Al+



Using two ions

Clock ion (Al^+) for very accurate spectroscopy
Logic ion (Be^+) for cooling and readout
Coulomb-force couples the motion of the ions
$\Rightarrow$ Cooling Be+ leads to cooling of Al+



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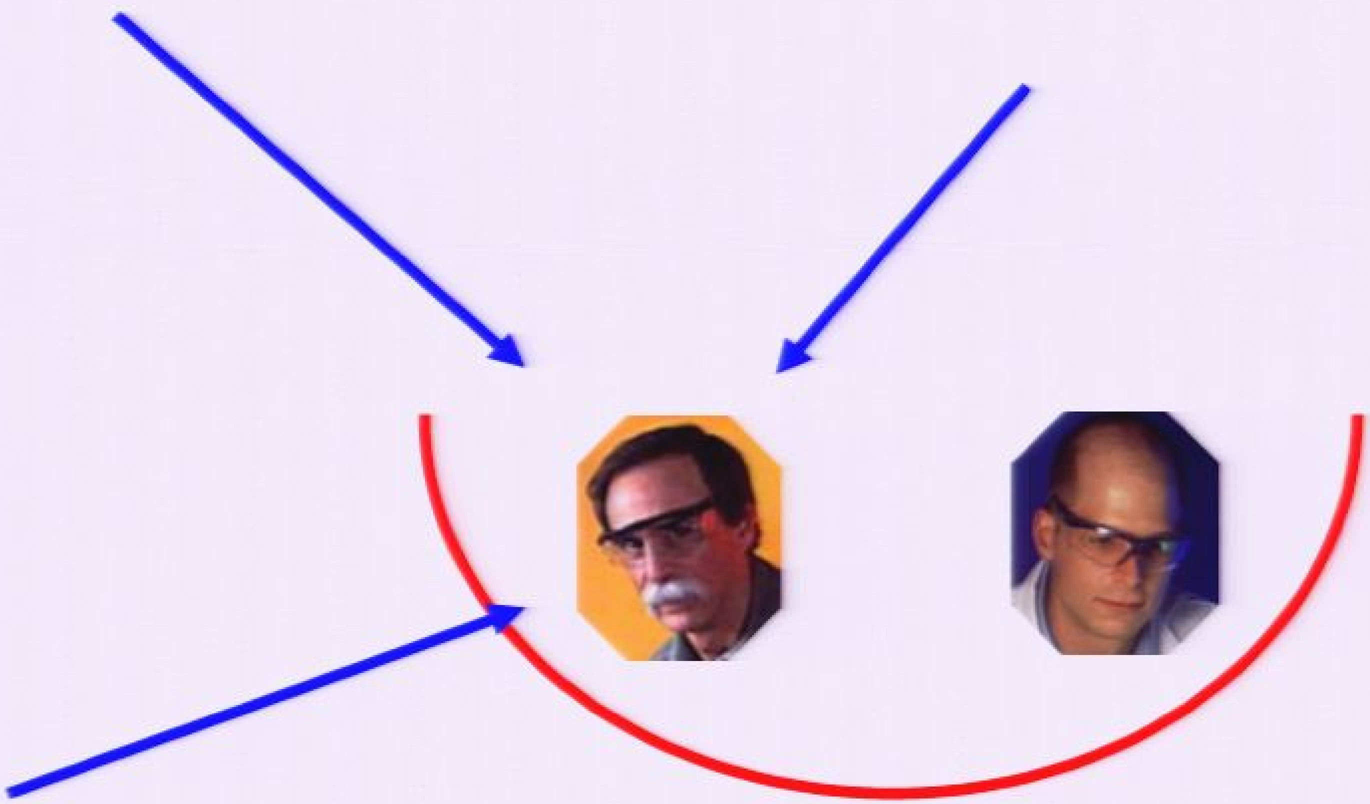

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Ion motion is quantized (n=0, 1, …)

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Transfer information Al^+ ⇨ Motion ⇨ Be^+

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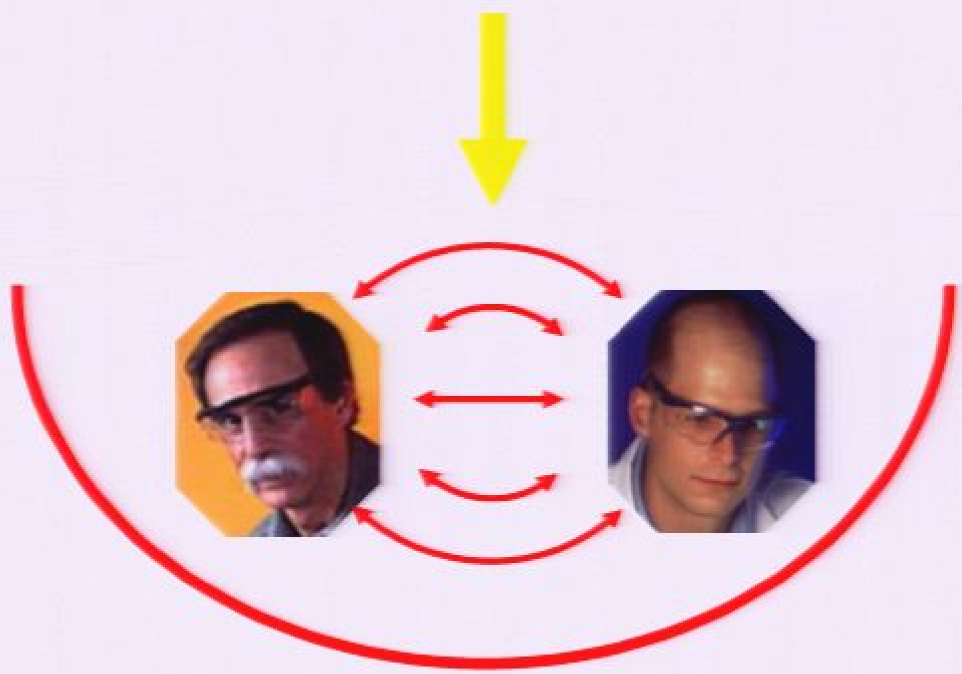

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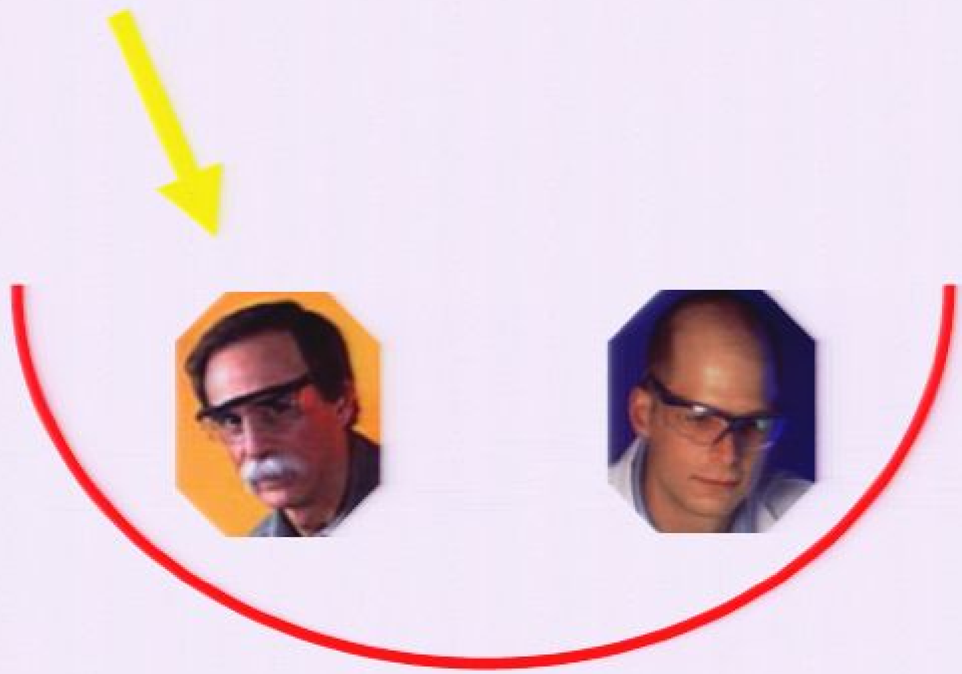
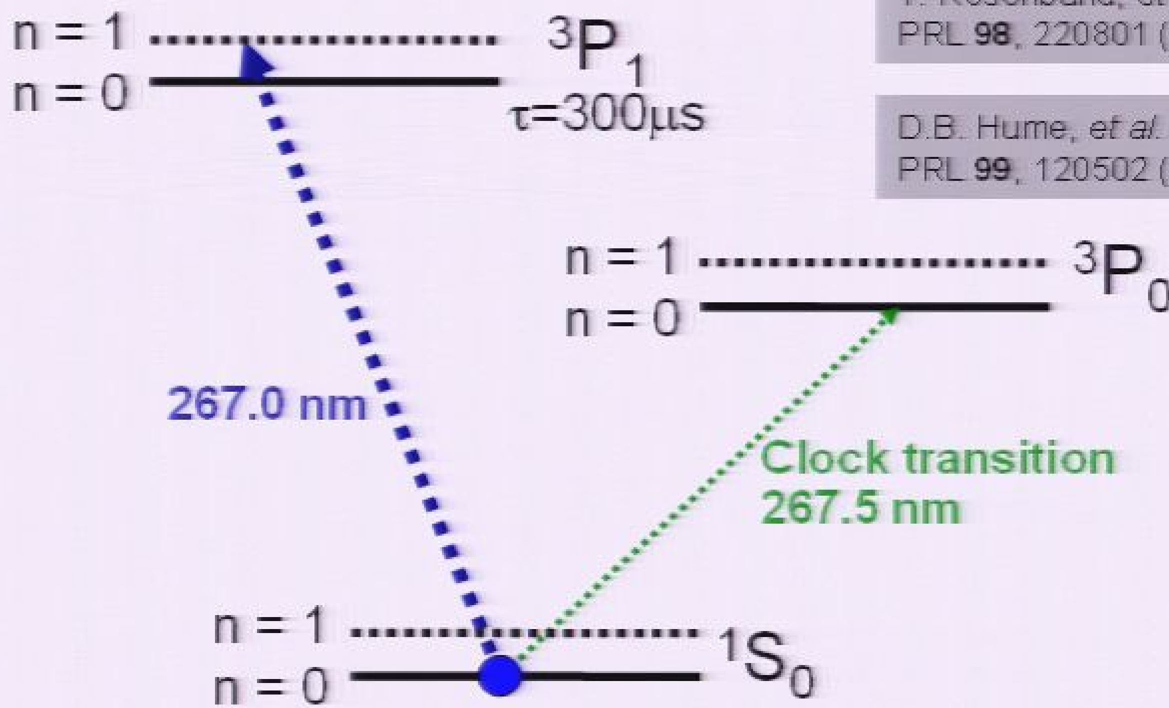


Quantum Logic Spectroscopy

$^{27}Al^+$

$^1S_0$, n = 0



P.O. Schmidt, *et al.* *Science* **309**, 749 (2005)

T. Rosenband, *et al.* PRL **98**, 220801 (2007)

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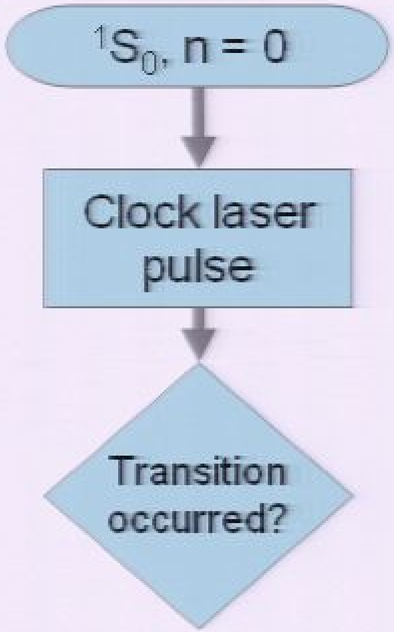

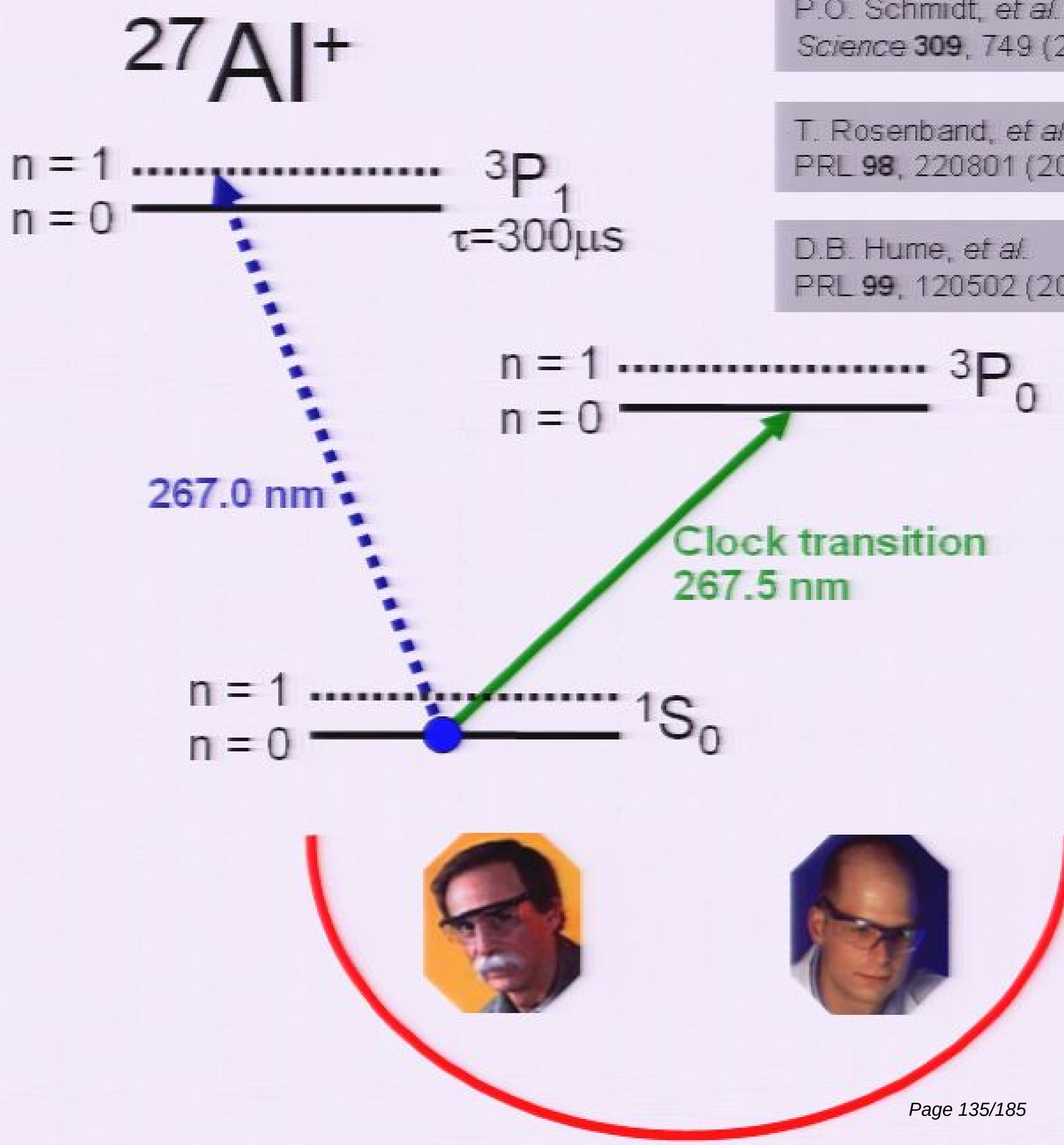

Quantum Logic Spectroscopy

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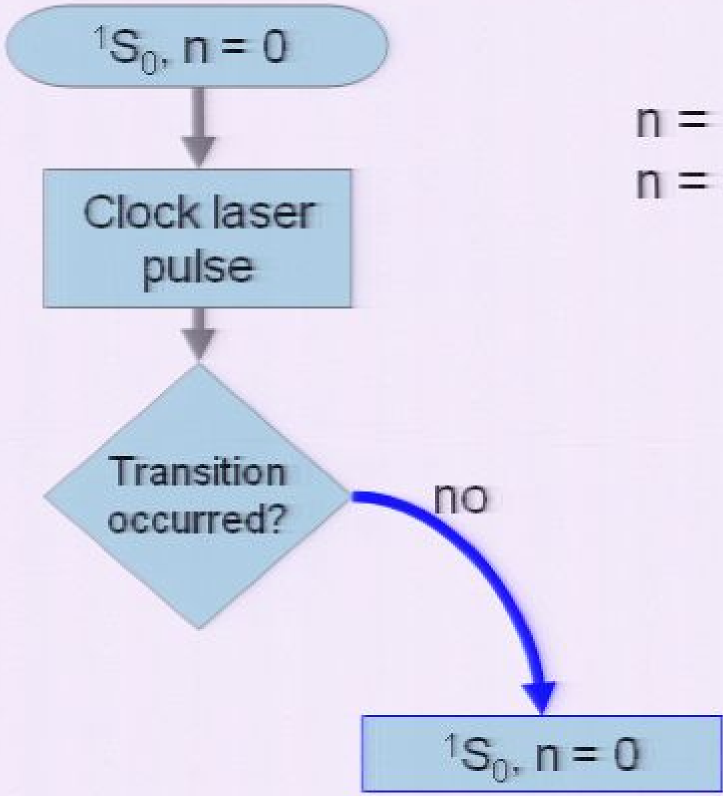

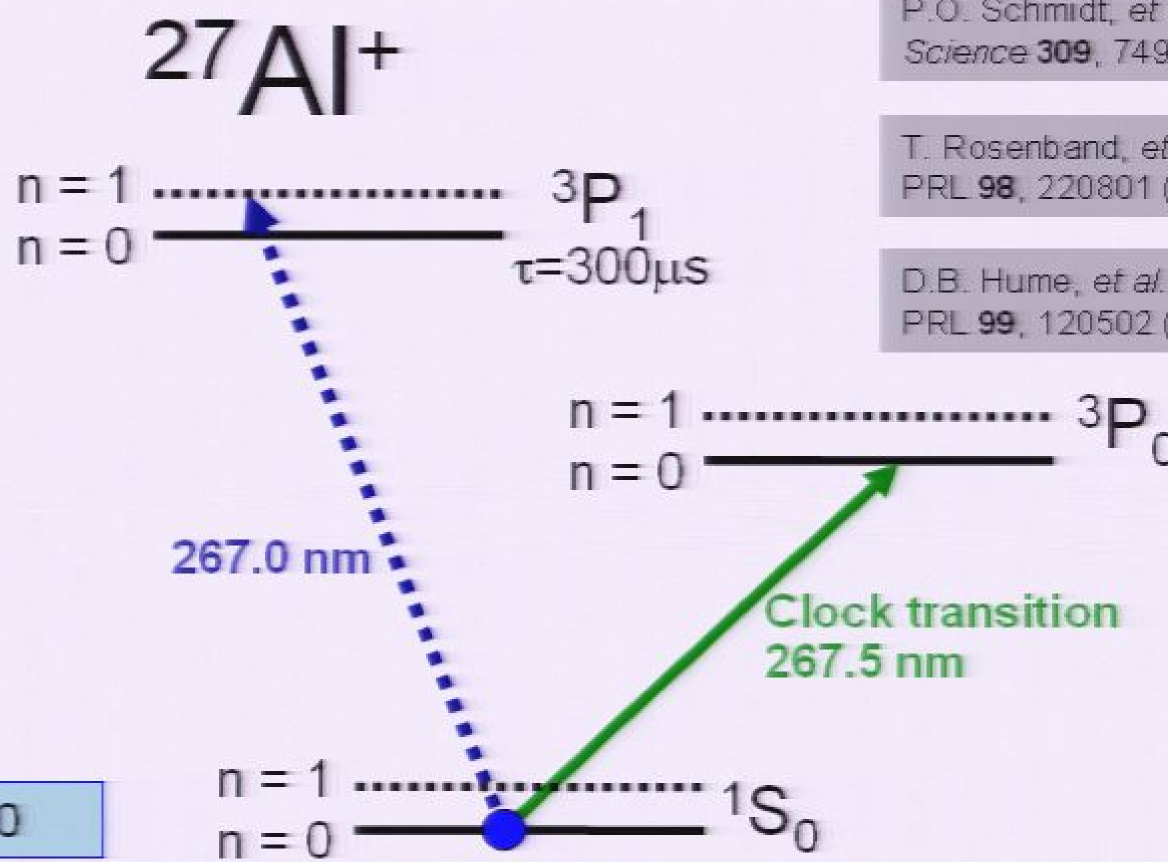

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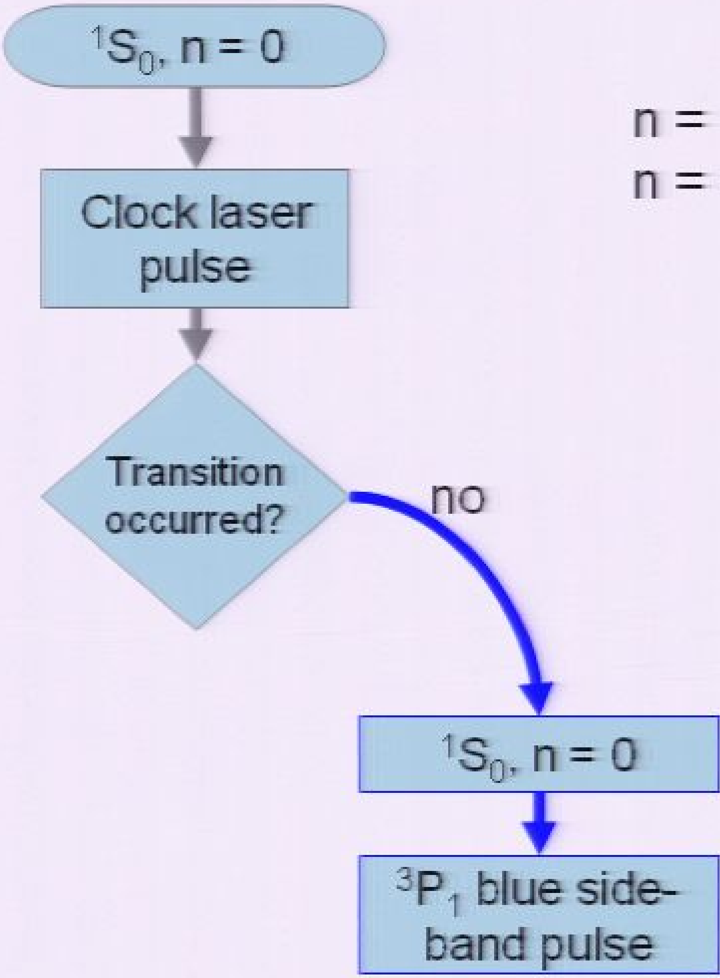
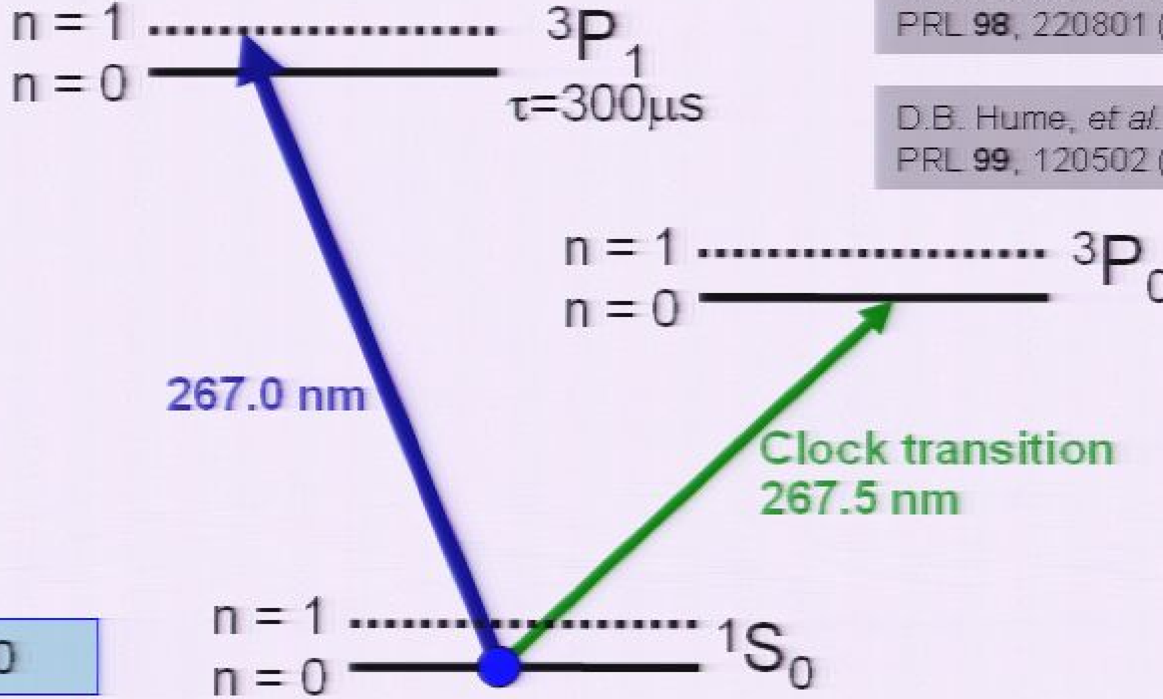
$^{27}Al^{+}$





Quantum Logic Spectroscopy

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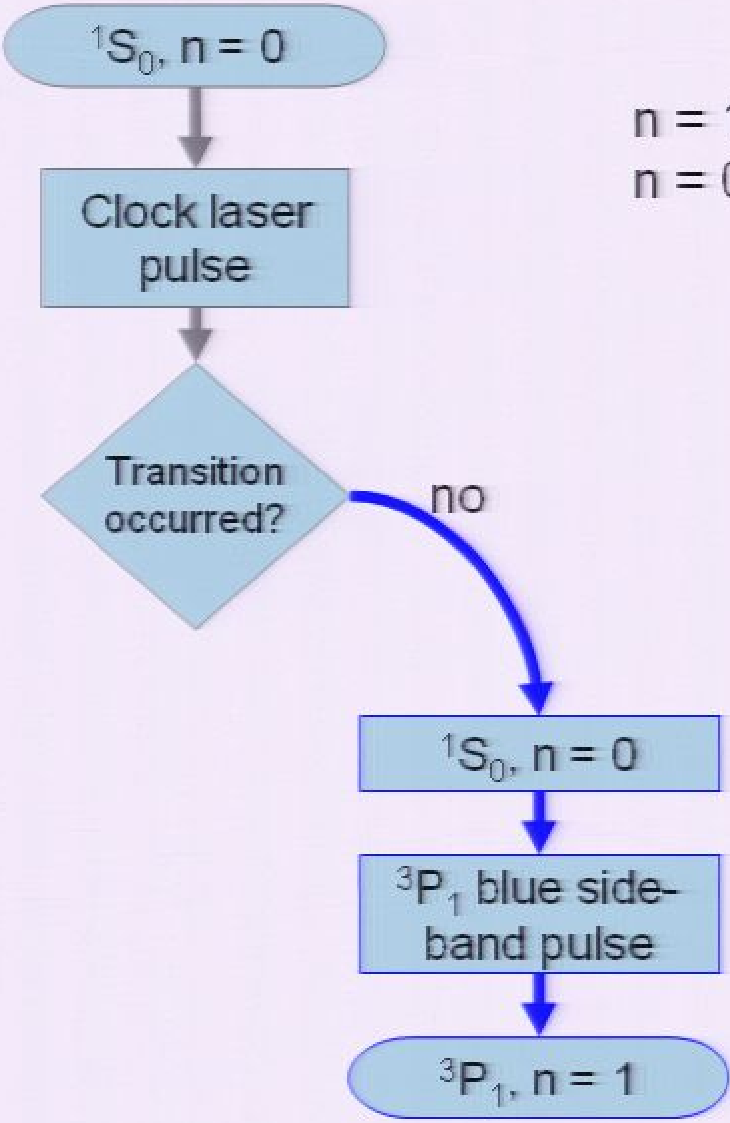

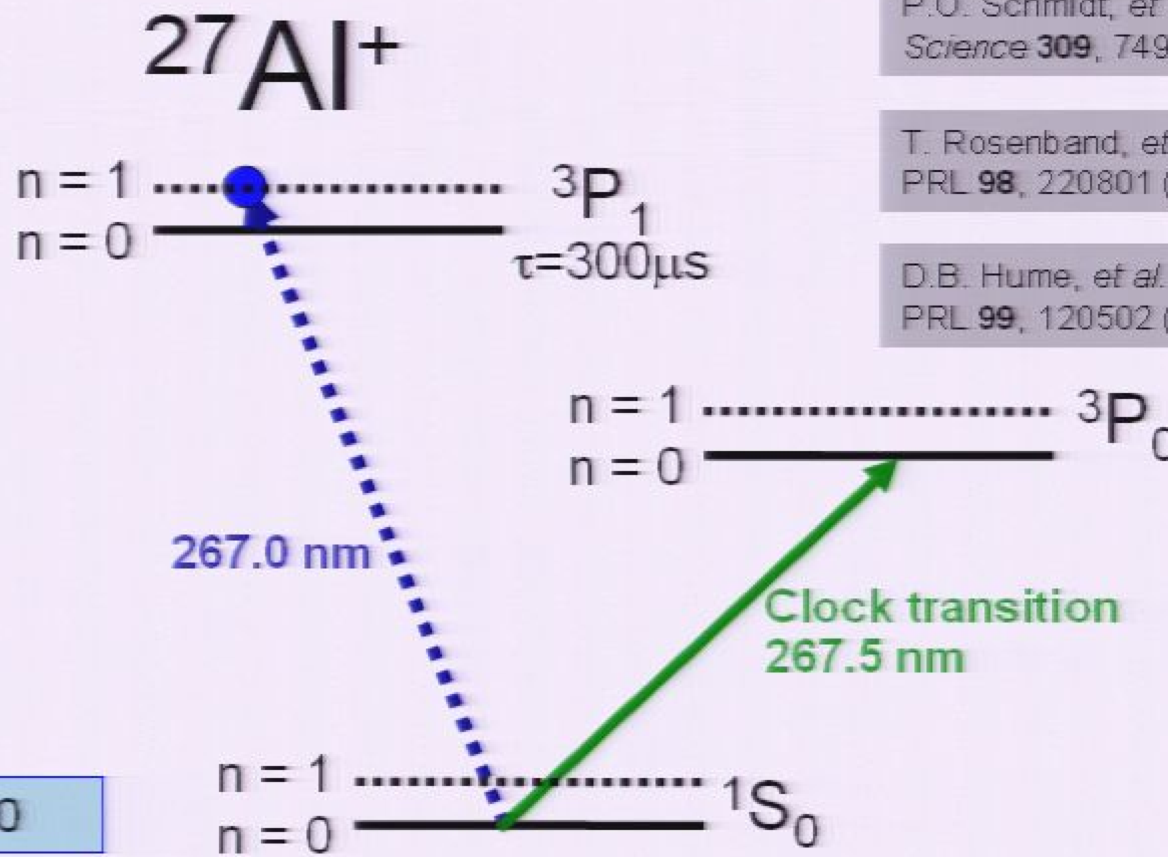

Quantum Logic Spectroscopy

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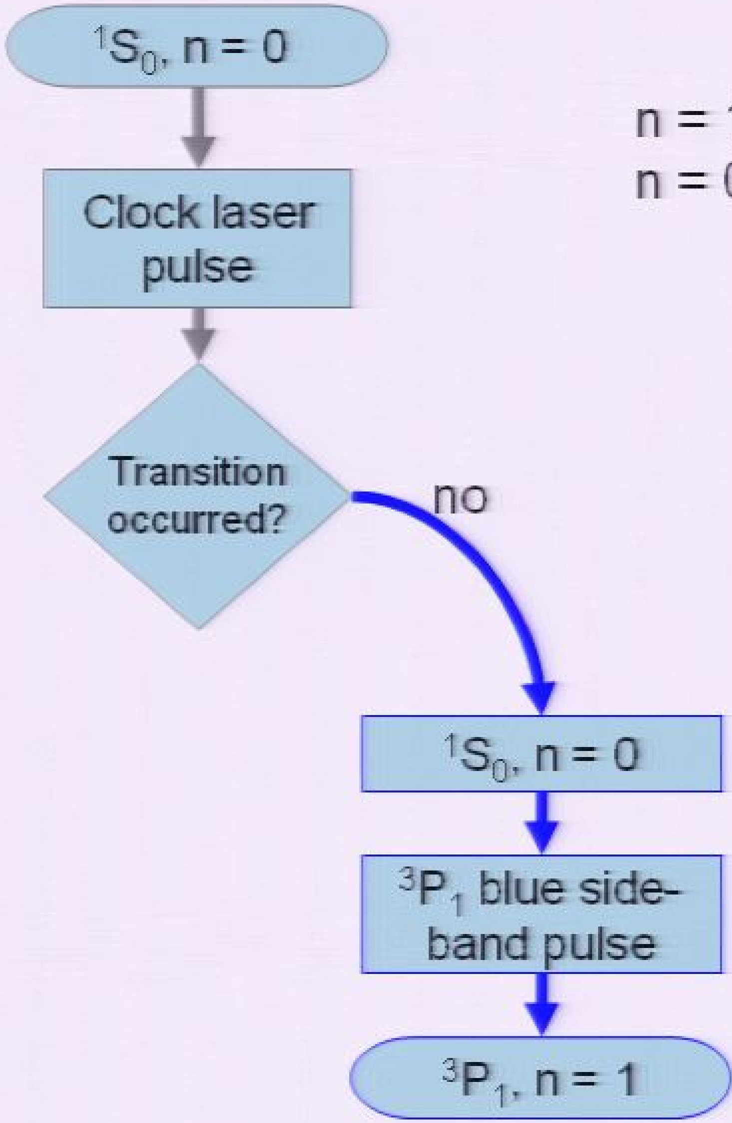
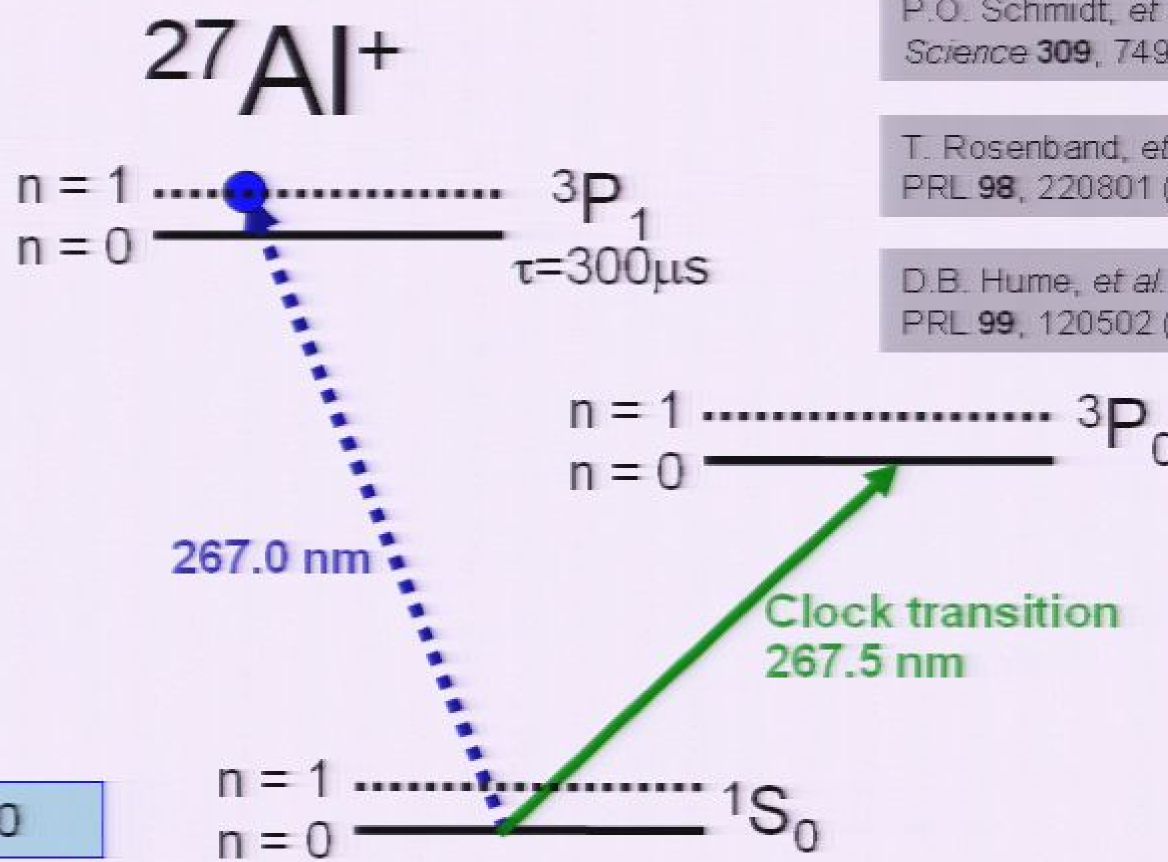
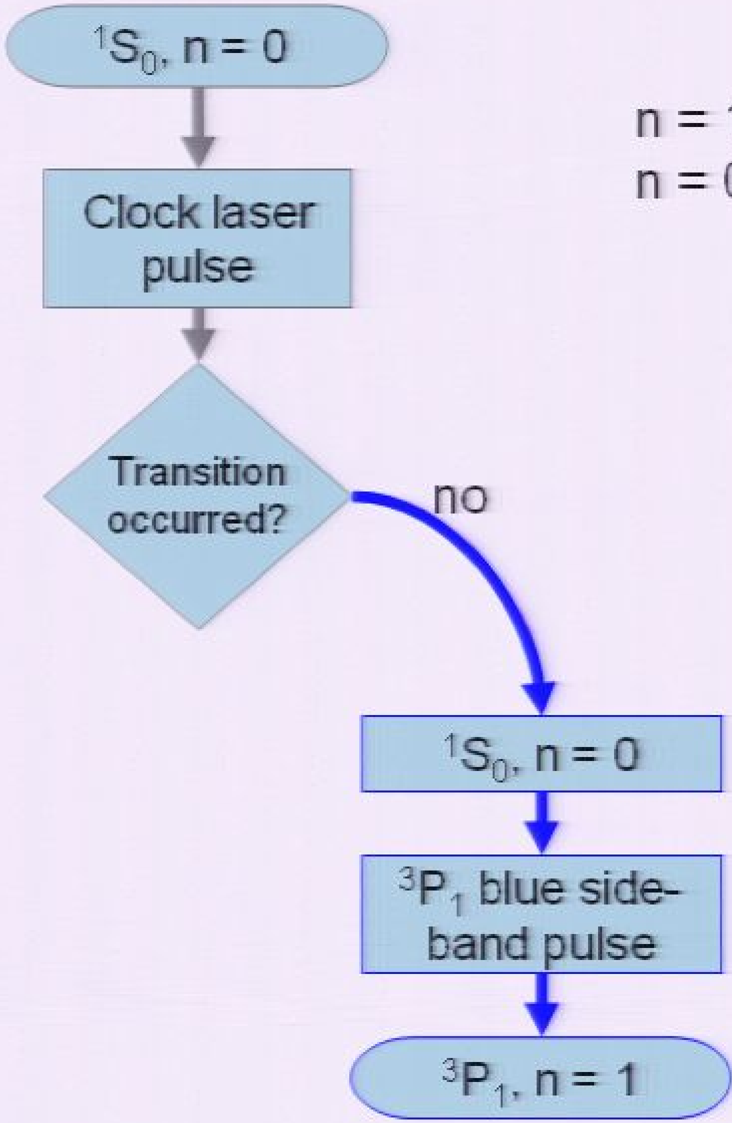
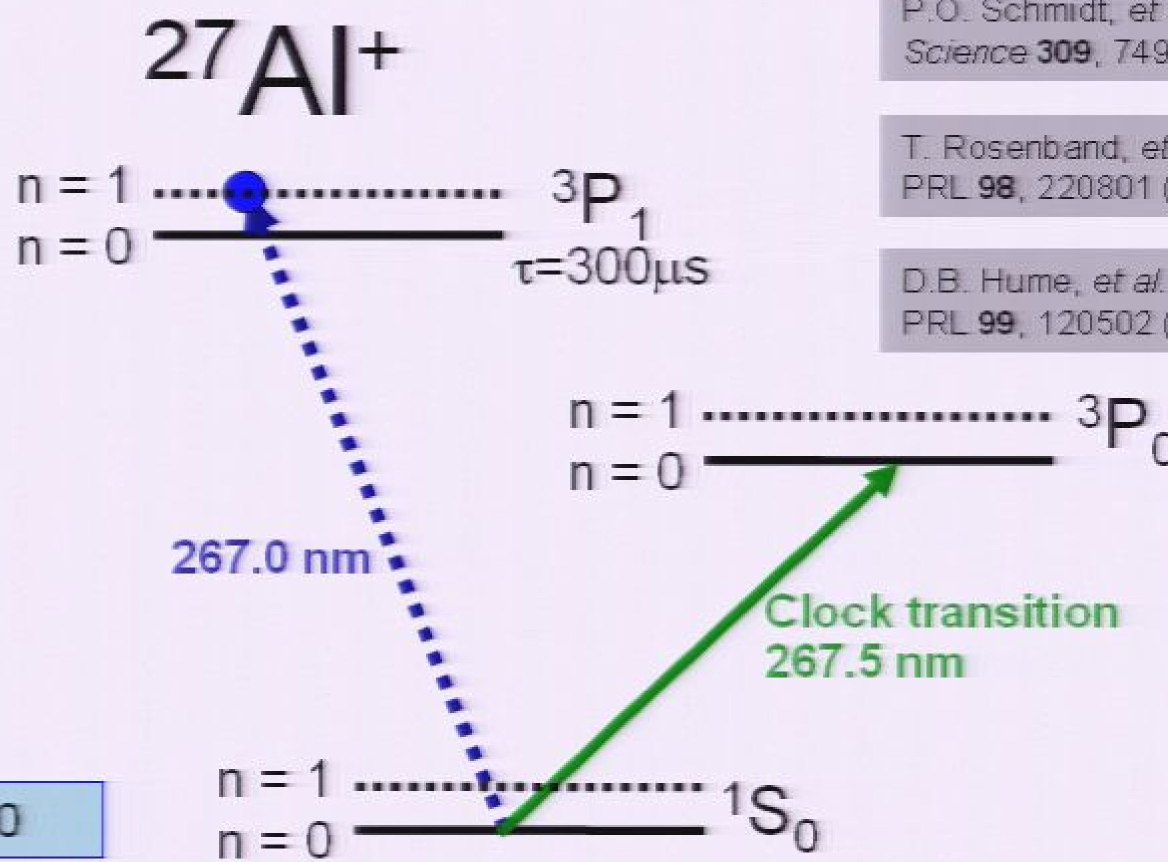




Quantum Logic Spectroscopy





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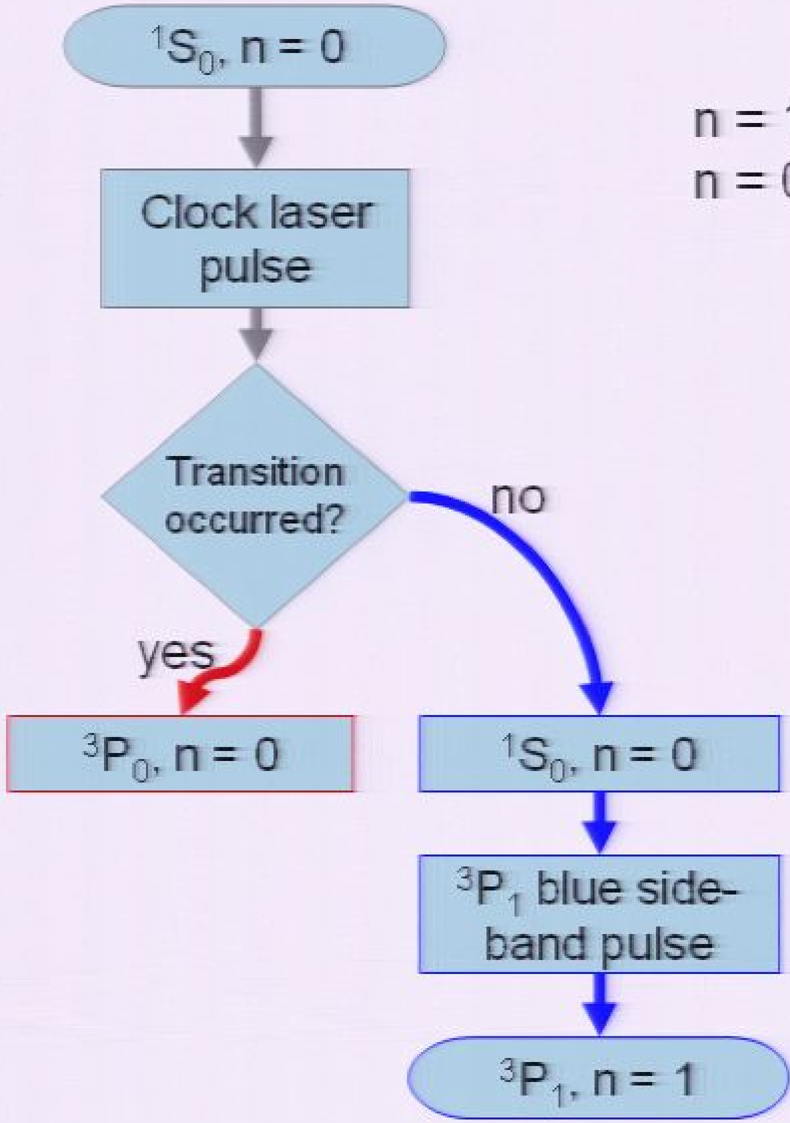
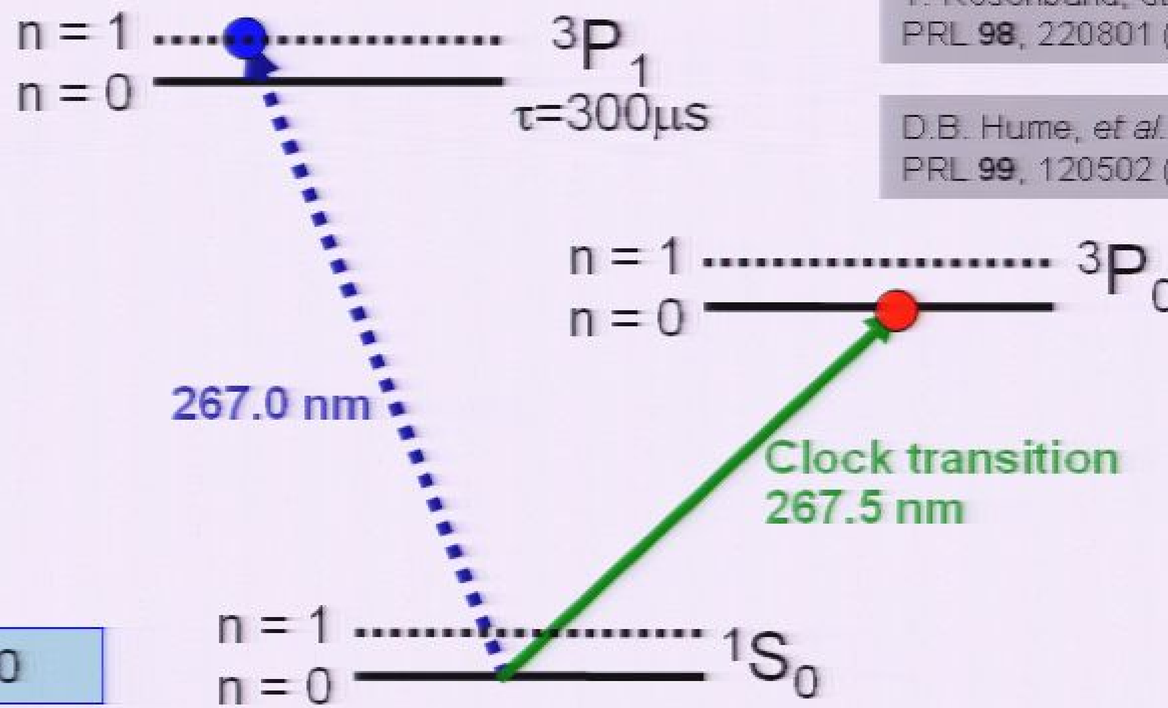


$^{27}Al^+$



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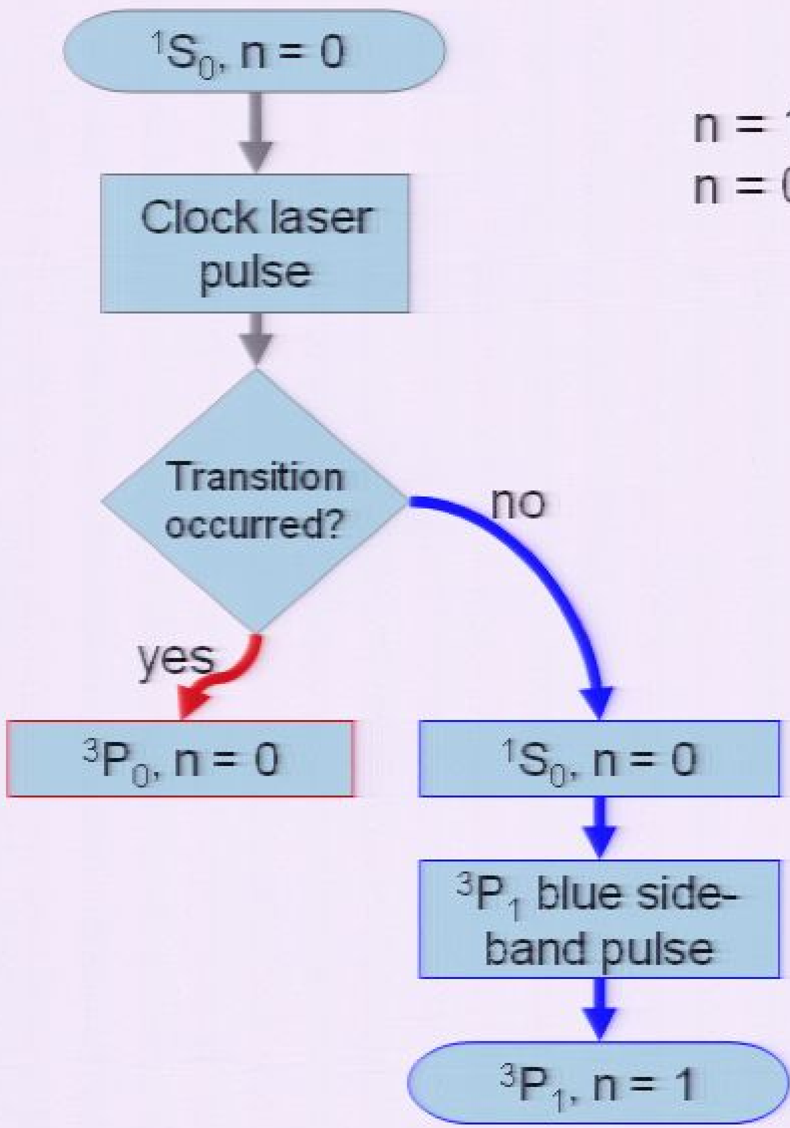
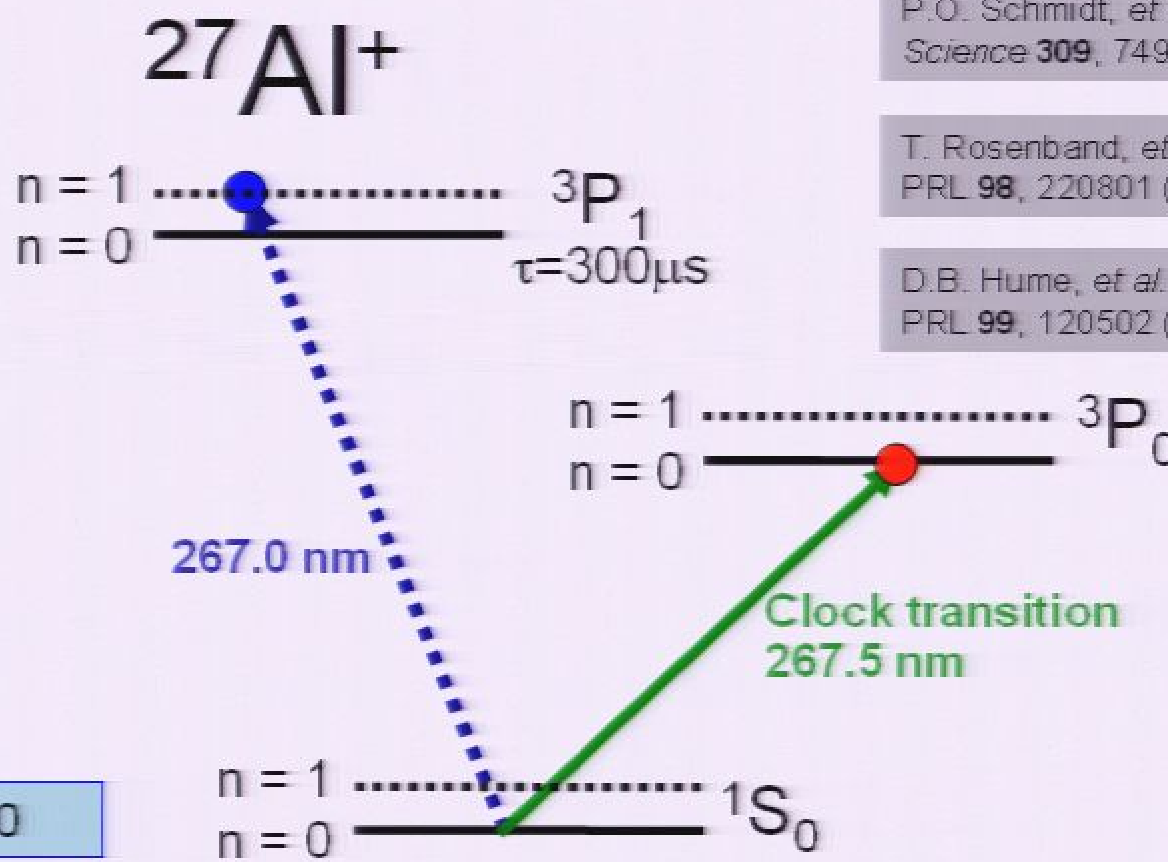
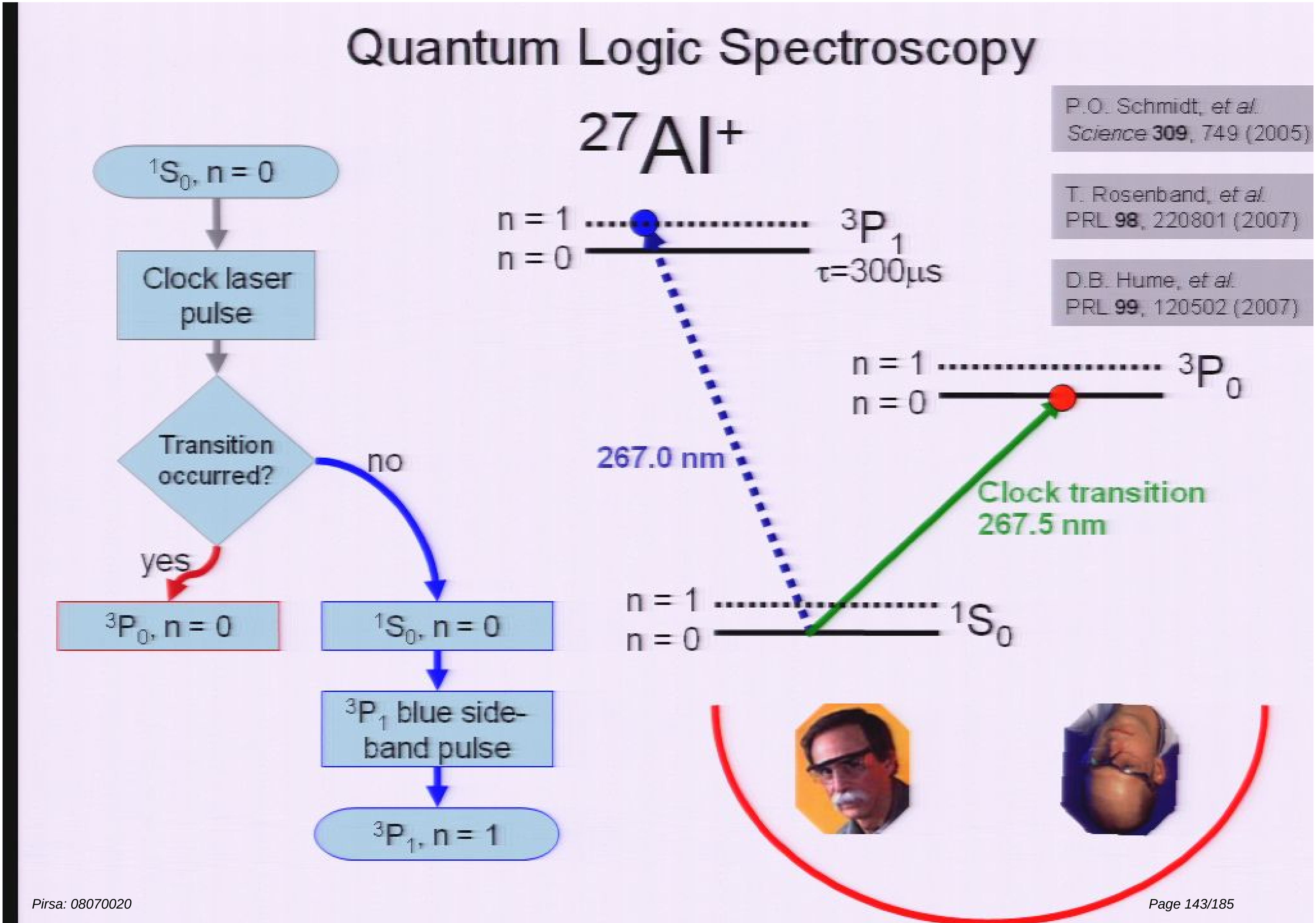
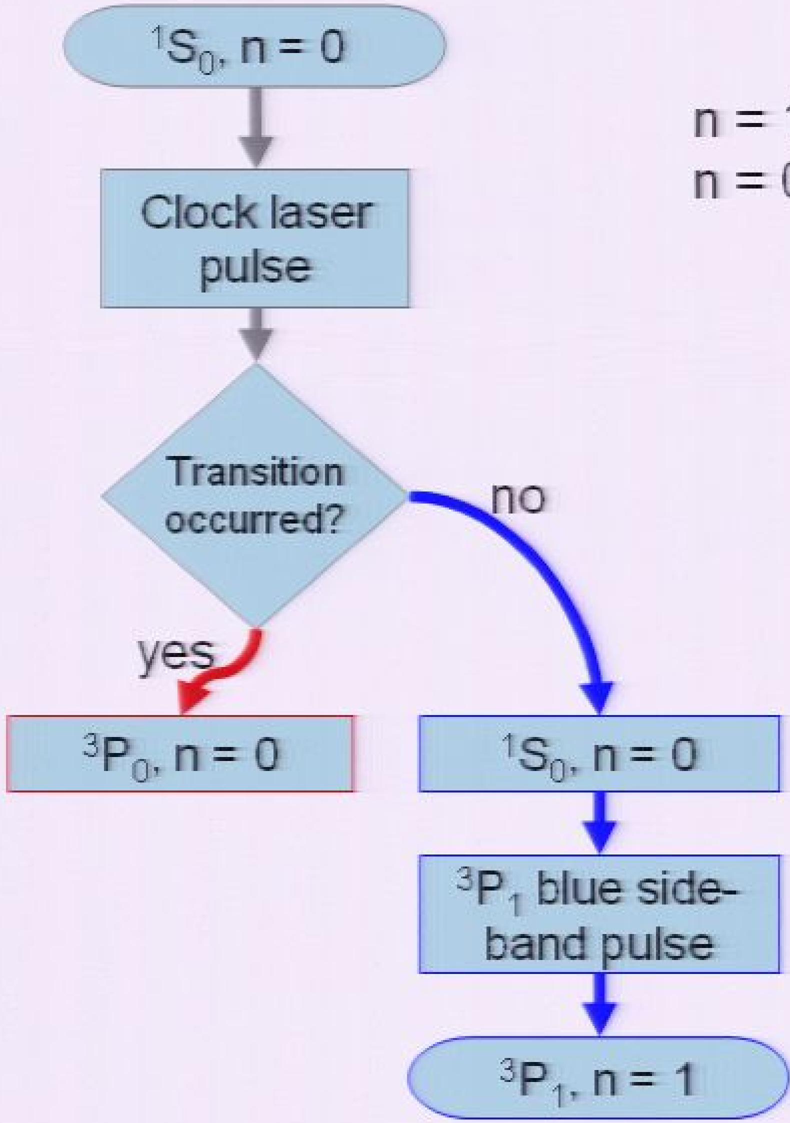
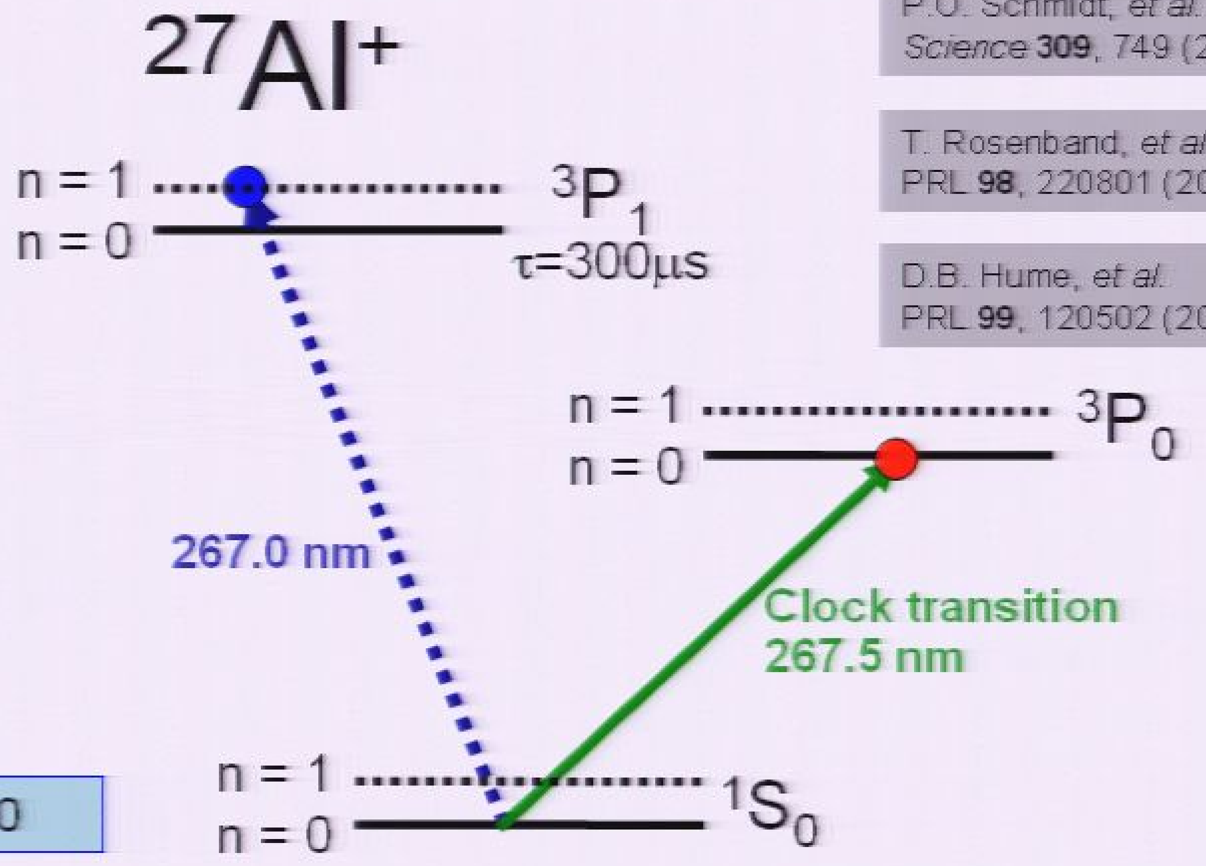





Quantum Logic Spectroscopy
27Al+
P.O. Schmidt, et al. Science 309, 749 (2005)
T. Rosenband, et al. PRL 98, 220801 (2007)
D.B. Hume, et al. PRL 99, 120502 (2007)
1S0, n = 0
Clock laser pulse
Transition occurred?
no
yes
3P0, n = 0
1S0, n = 0
3P1 blue side-band pulse
3P1, n = 1
n = 1
n = 0
3P1
τ=300μs
267.0 nm
n = 1
n = 0
3P0
Clock transition 267.5 nm
n = 1
n = 0
1S0

Quantum Logic Spectroscopy





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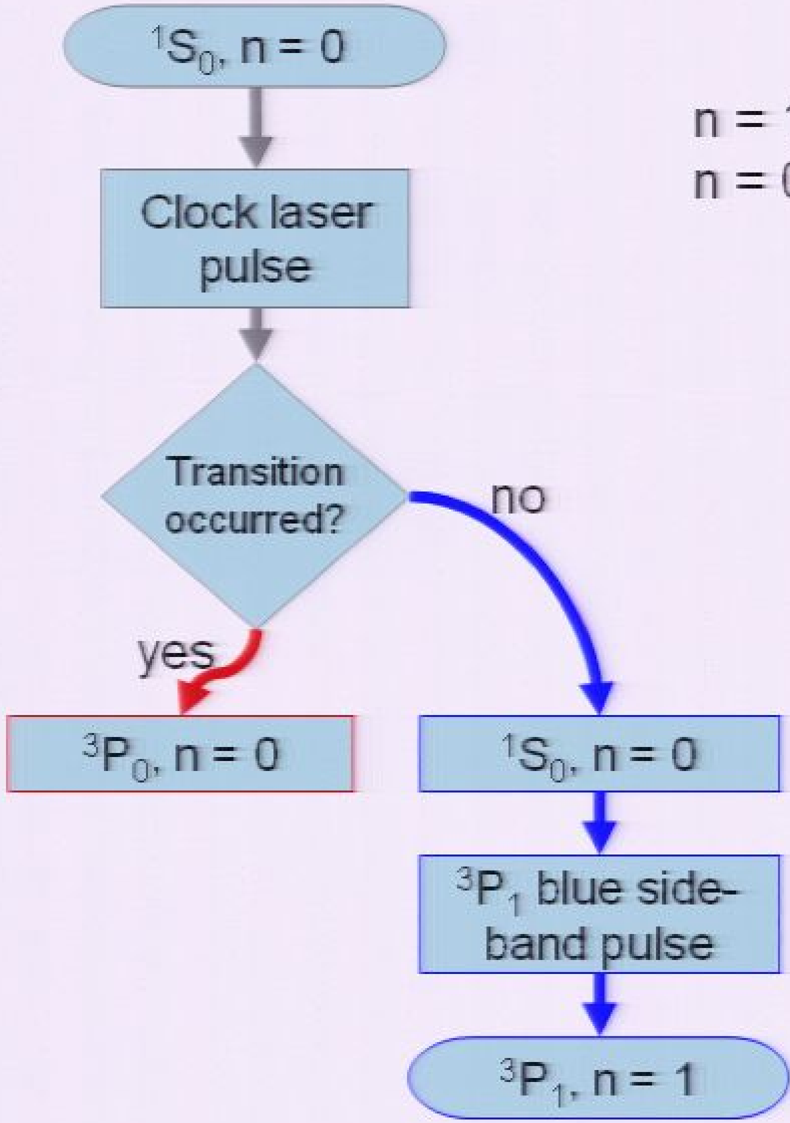
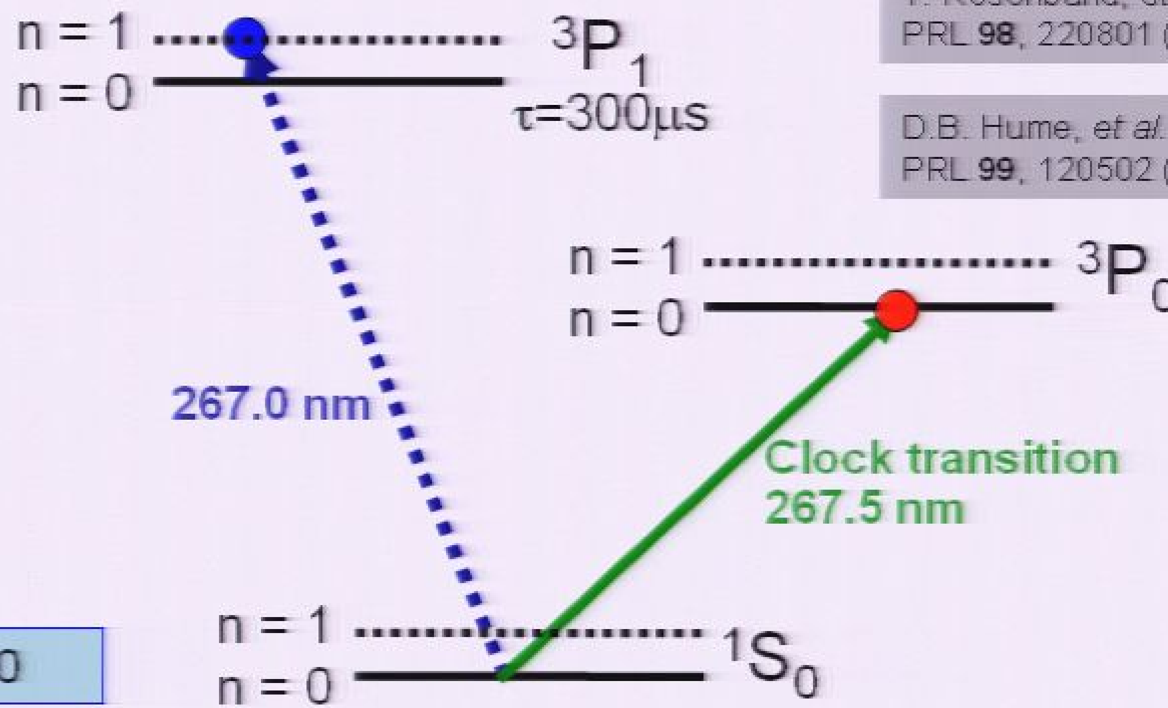


$^{27}Al^+$



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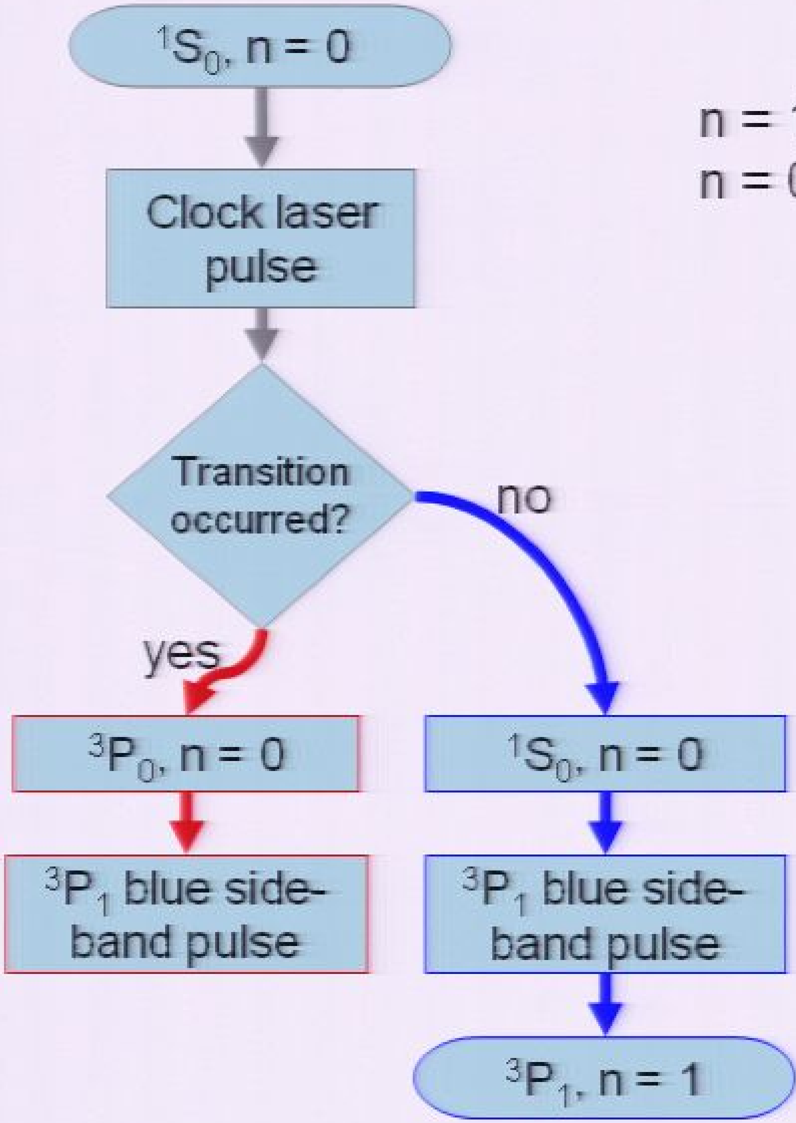
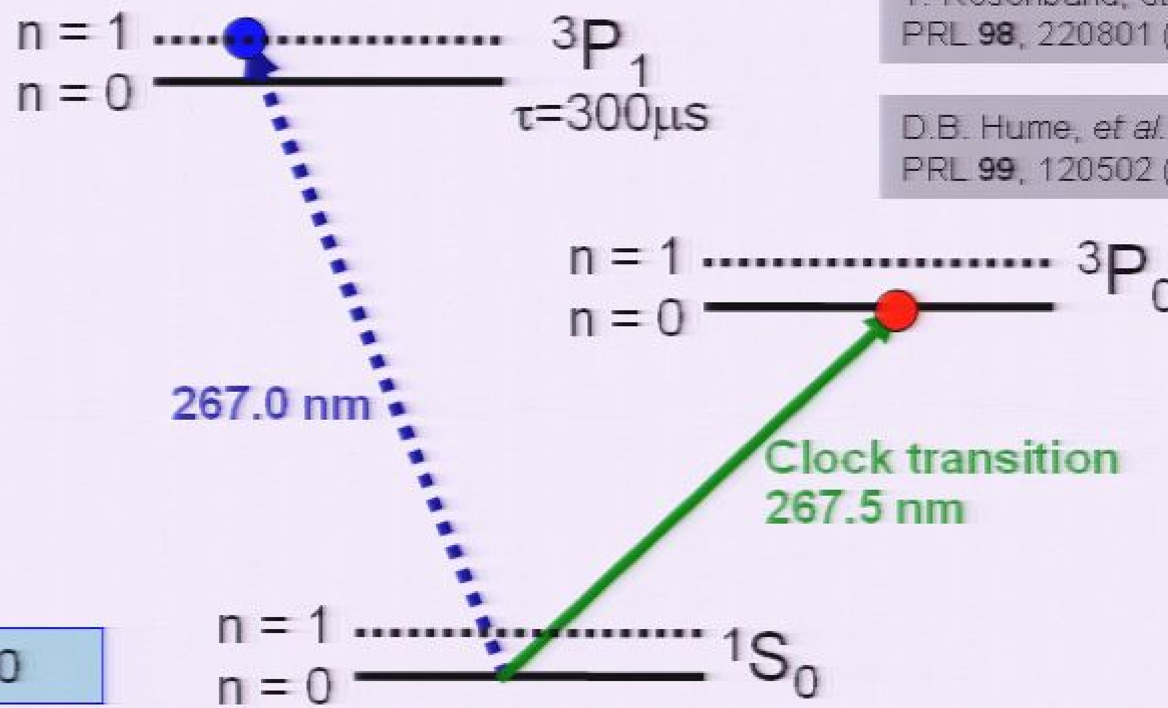


$^{27}Al^+$

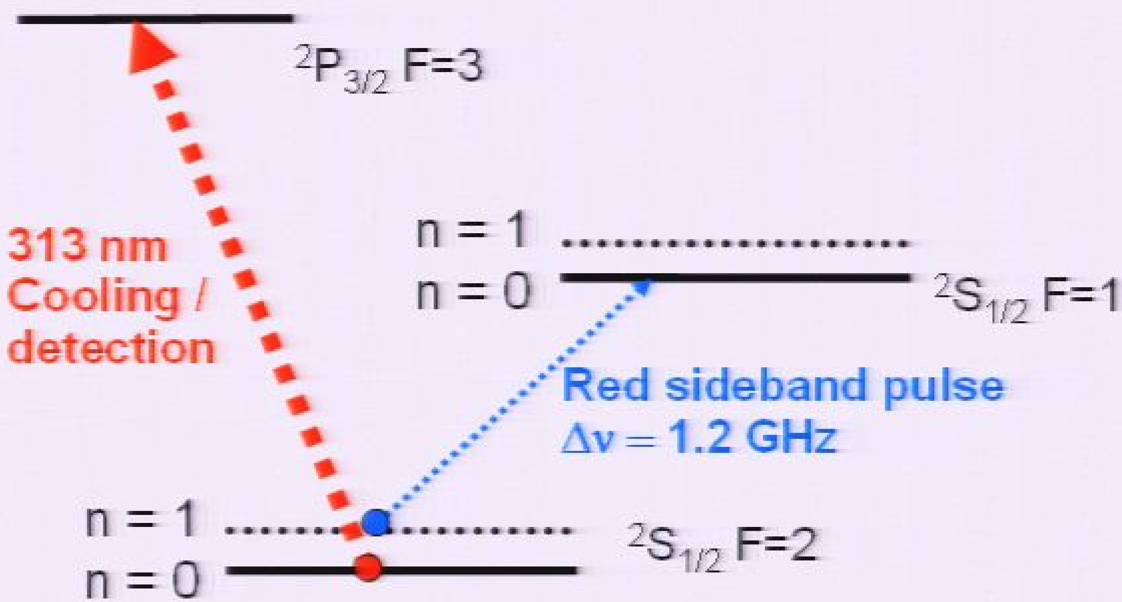


Single phonon detection

$^{27}Al^+ \; ^3P_0$
$n = 0$

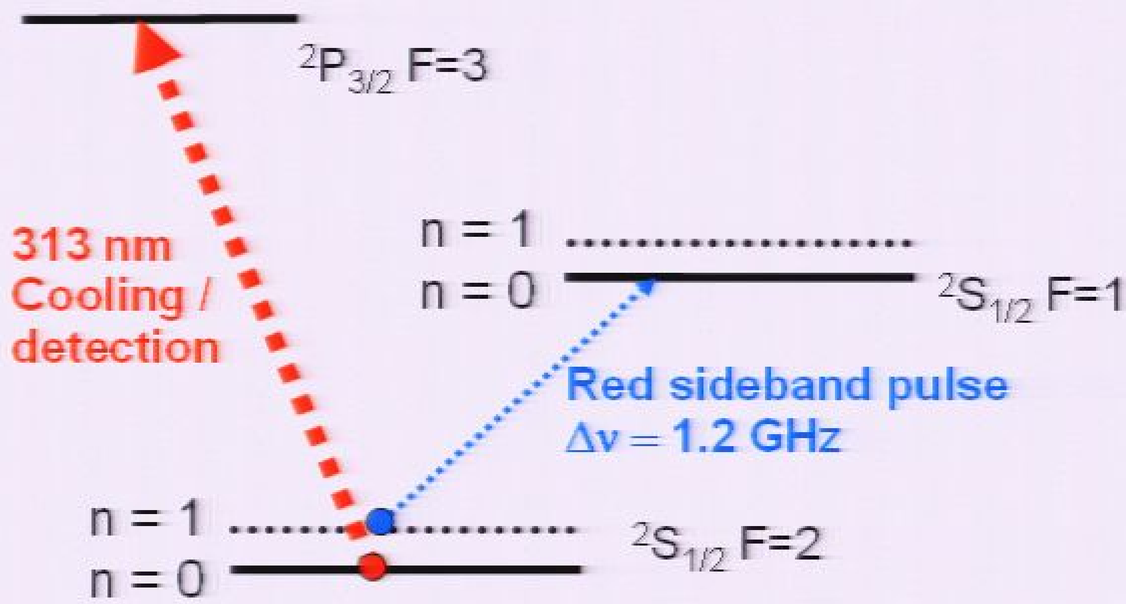
$^{27}Al^+ \; ^1S_0$
$n = 1$

$^9Be^+$



Single phonon detection

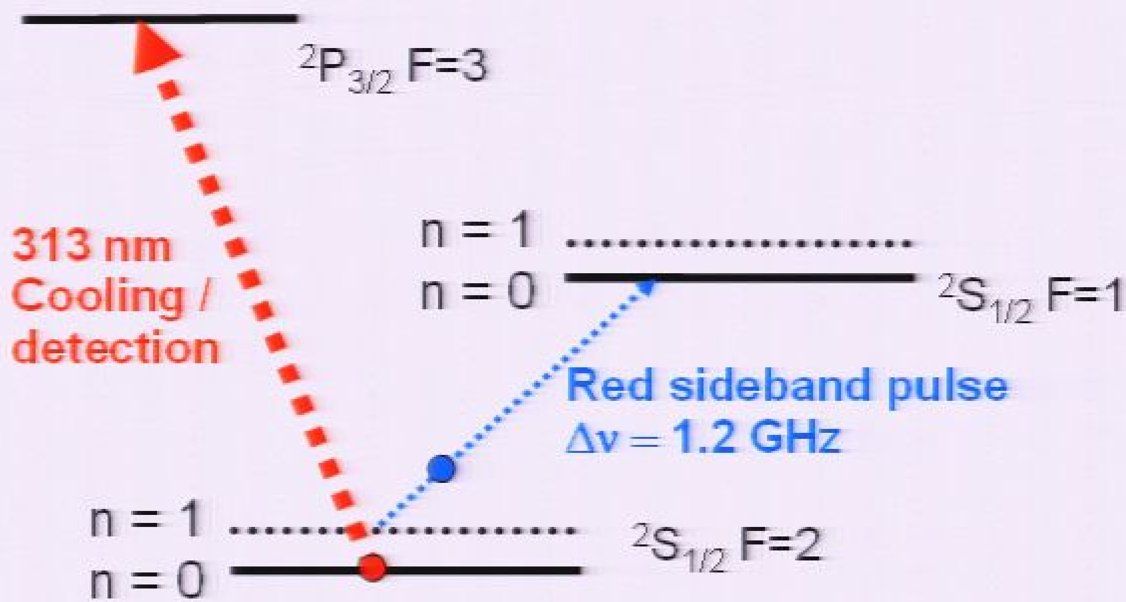
$^{9}Be^{+}$



Single phonon detection

$^{9}Be^{+}$

$^{27}Al^{+}\ ^{3}P_0$, n = 0	$^{27}Al^{+}\ ^{1}S_0$, n = 1
↓	↓
$^{9}Be^{+}\ ^{2}S_{1/2}$ F=2, n = 0	$^{9}Be^{+}\ ^{2}S_{1/2}$ F=2, n = 1
↓	↓
Red side-band pulse	Red side-band pulse



Single phonon detection

$^{9}Be^{+}$

$^{27}Al^{+}\ {}^{3}P_0$, n = 0	$^{27}Al^{+}\ {}^{1}S_0$, n = 1
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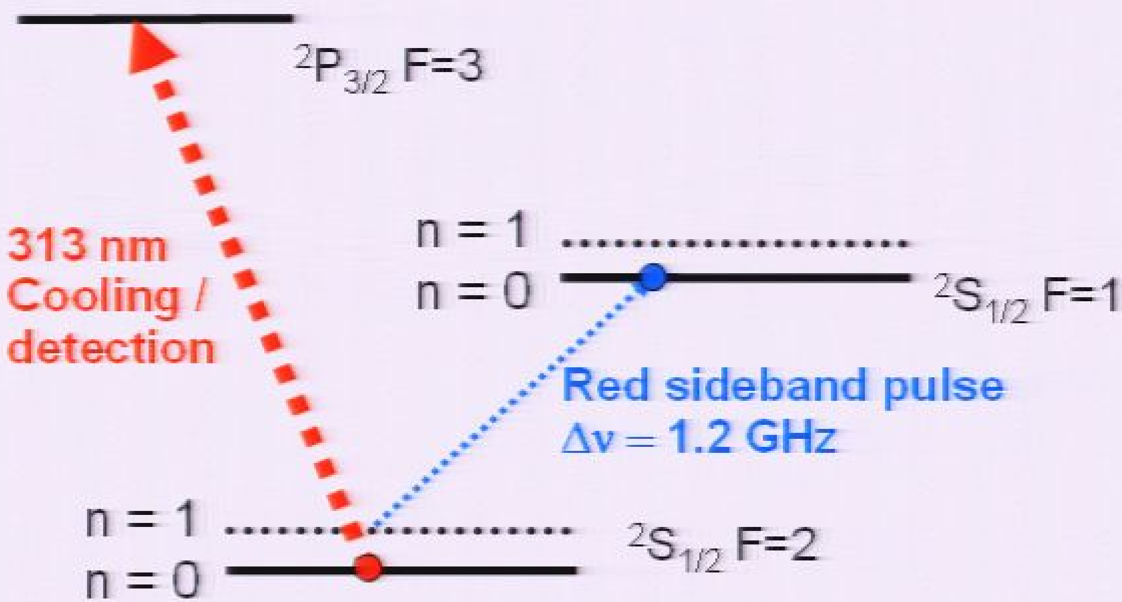
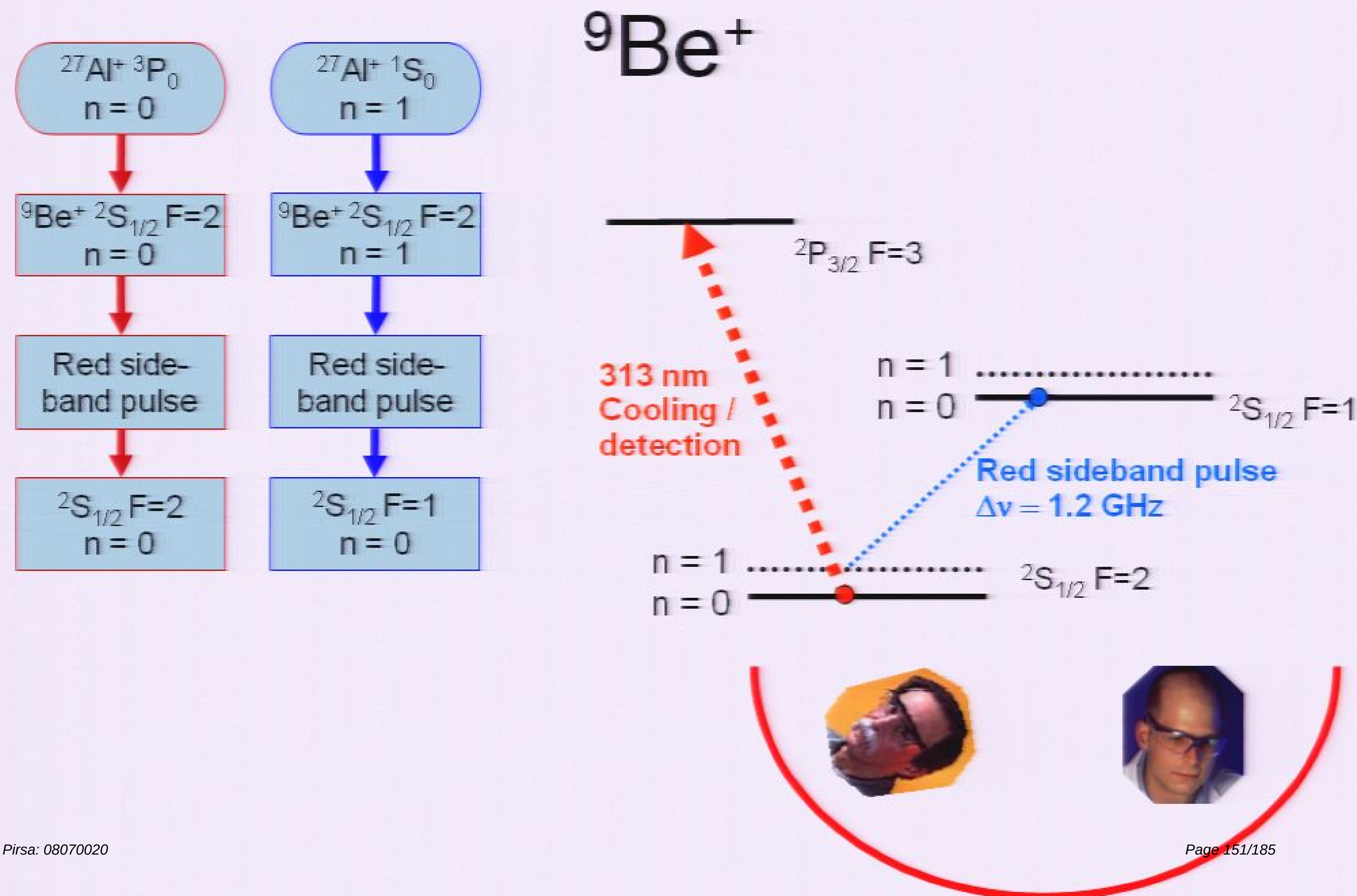
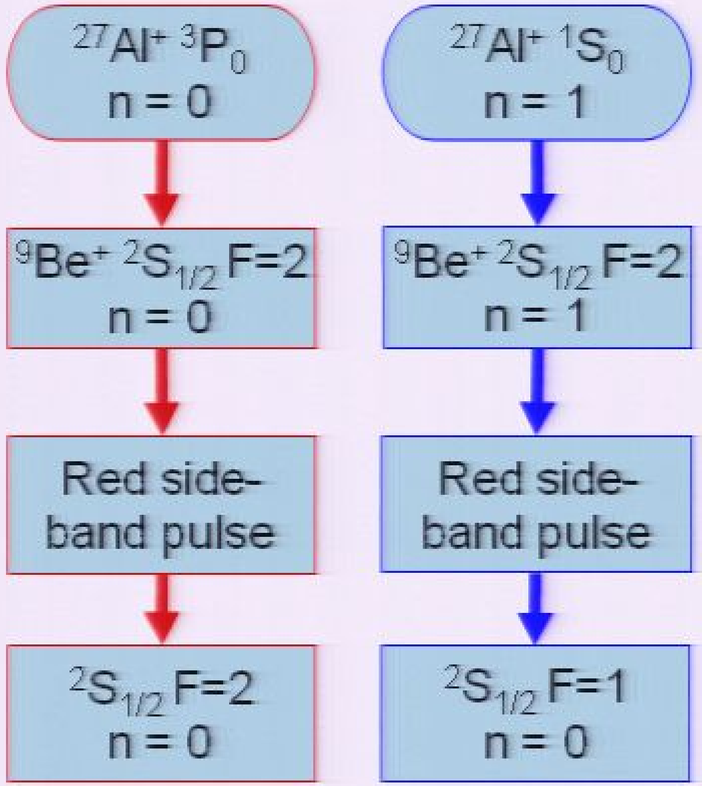
Red side-band pulse	Red side-band pulse

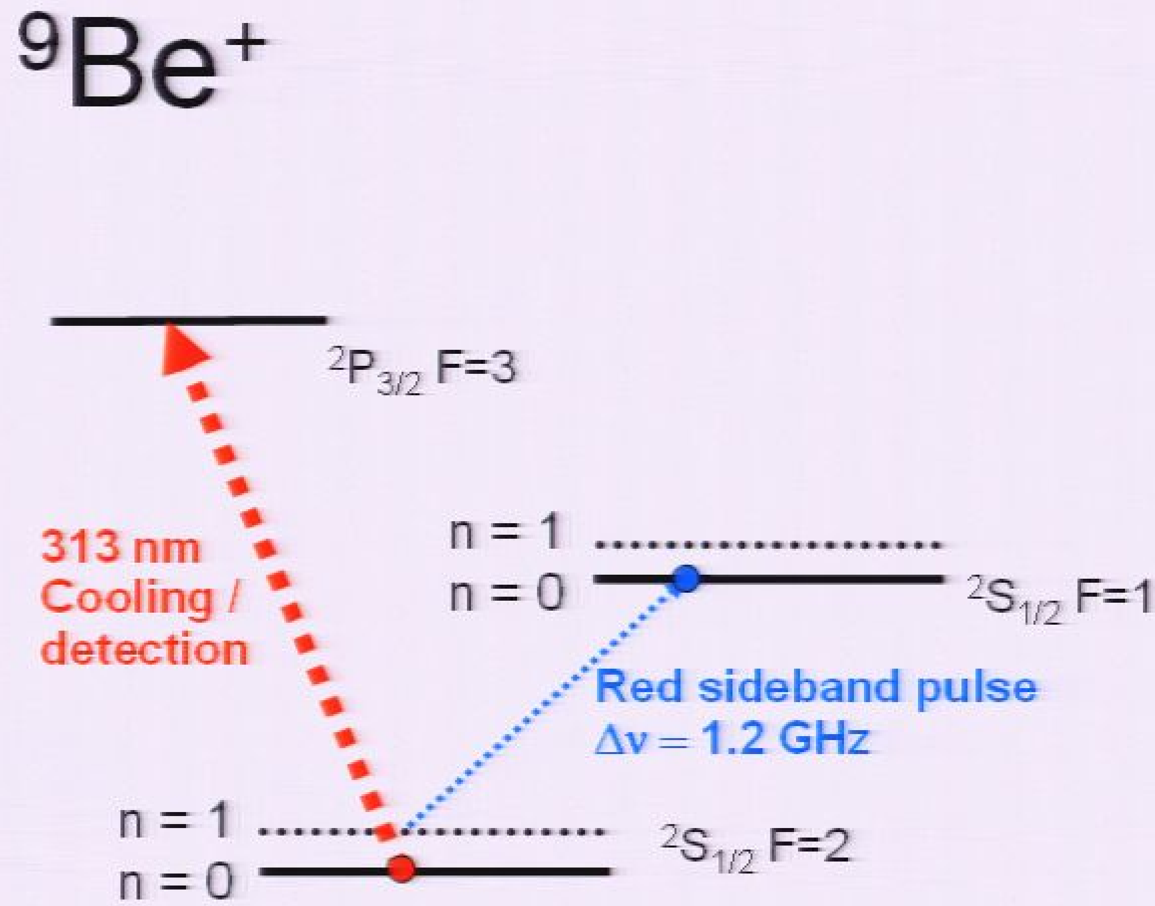


Single phonon detection



Single phonon detection



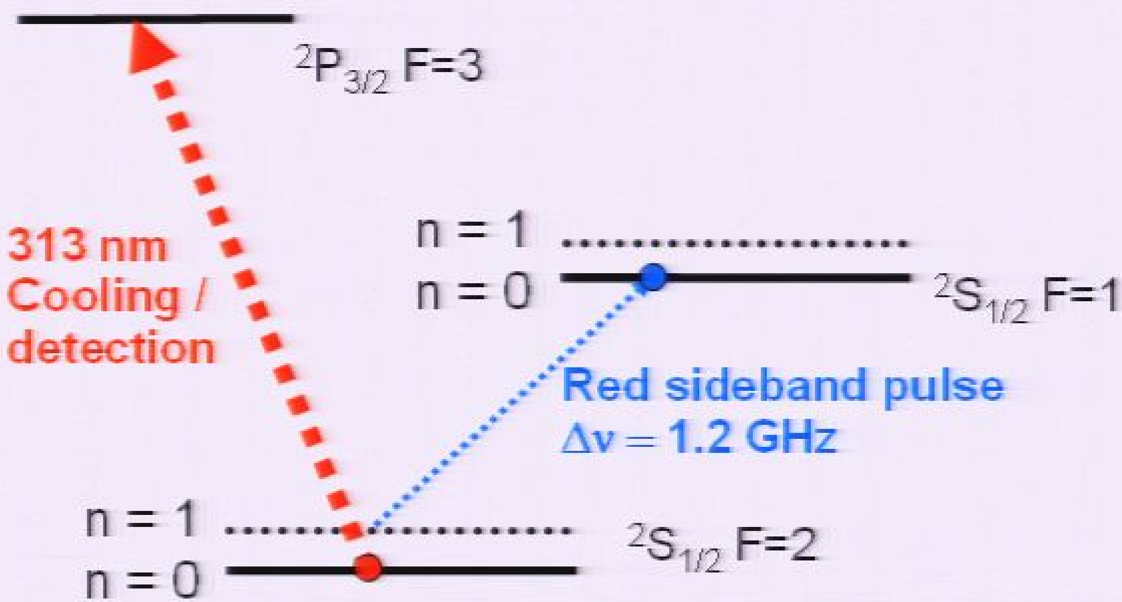


Single phonon detection

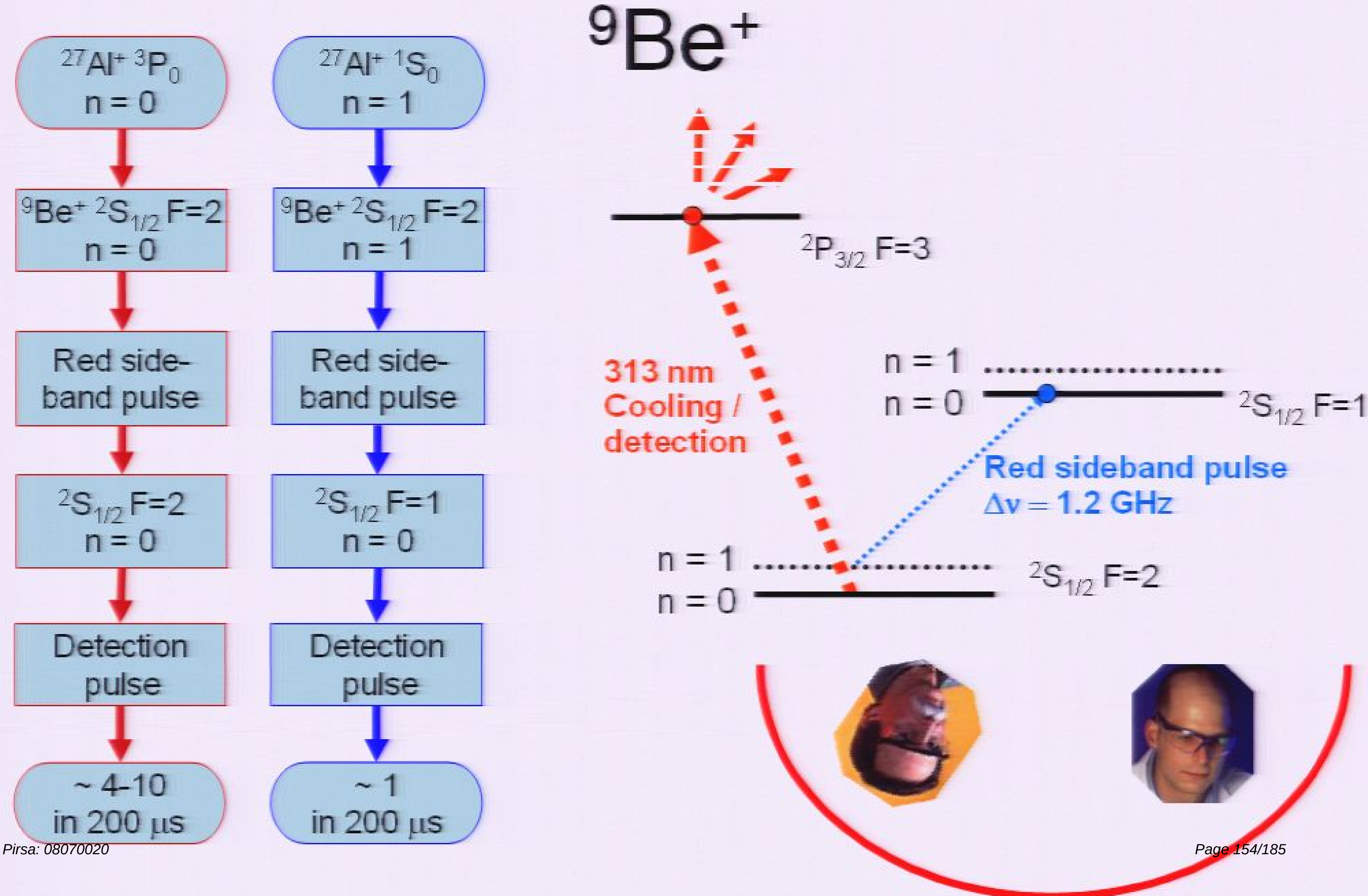
$^{9}Be^{+}$

$^{27}Al^{+}\ {}^{3}P_0$, n = 0
↓
$^{9}Be^{+}\ {}^{2}S_{1/2}$ F=2, n = 0
↓
Red side-band pulse
↓
$^{2}S_{1/2}$ F=2, n = 0
↓
Detection pulse

$^{27}Al^{+}\ {}^{1}S_0$, n = 1
↓
$^{9}Be^{+}\ {}^{2}S_{1/2}$ F=2, n = 1
↓
Red side-band pulse
↓
$^{2}S_{1/2}$ F=1, n = 0
↓
Detection pulse

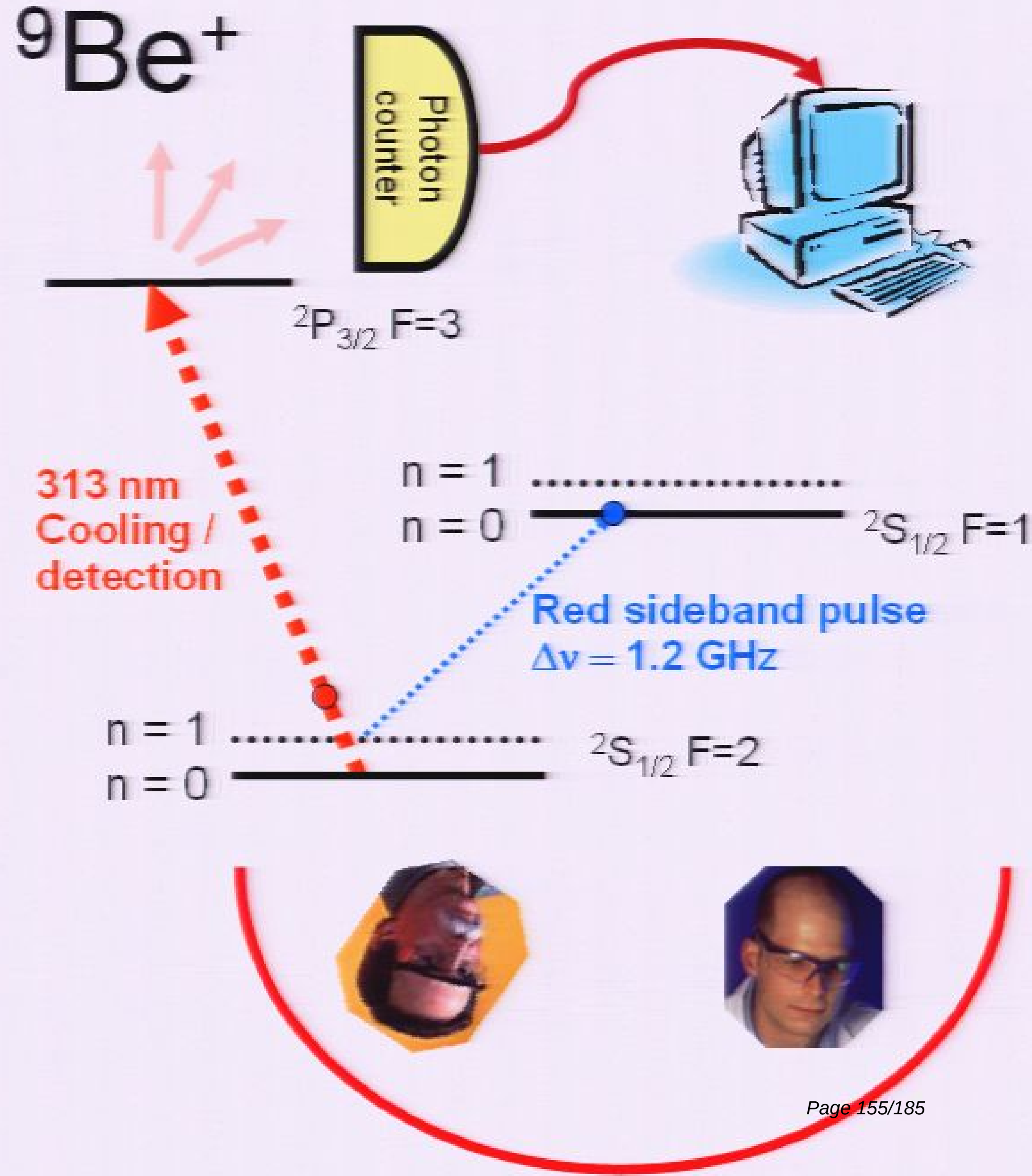


Single phonon detection



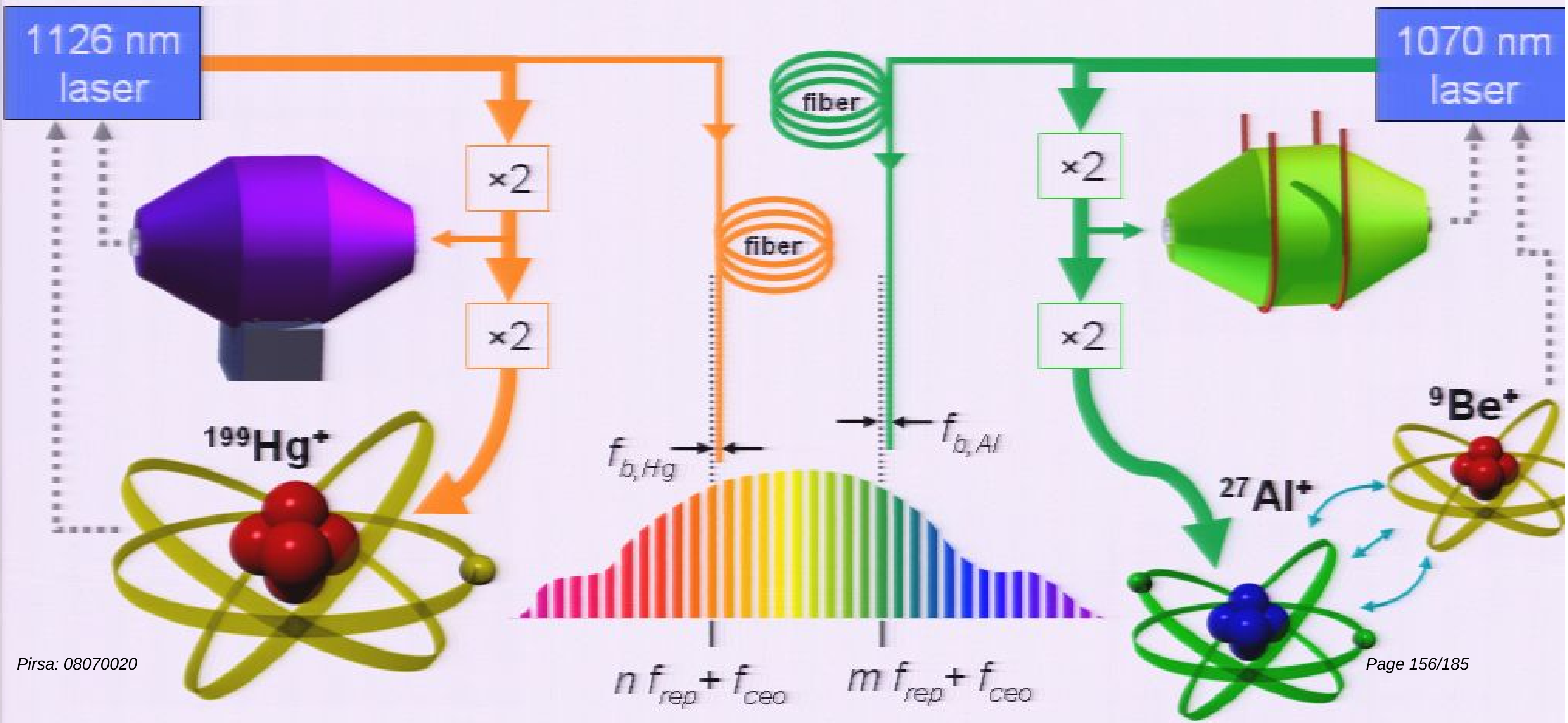
Single phonon detection

$^{27}Al^{+}\ ^{3}P_{0}$, n = 0	$^{27}Al^{+}\ ^{1}S_{0}$, n = 1
$^{9}Be^{+}\ ^{2}S_{1/2}$ F=2, n = 0	$^{9}Be^{+}\ ^{2}S_{1/2}$ F=2, n = 1
Red side-band pulse	Red side-band pulse
$^{2}S_{1/2}$ F=2, n = 0	$^{2}S_{1/2}$ F=1, n = 0
Detection pulse	Detection pulse
~ 4-10 in 200 µs	~ 1 in 200 µs



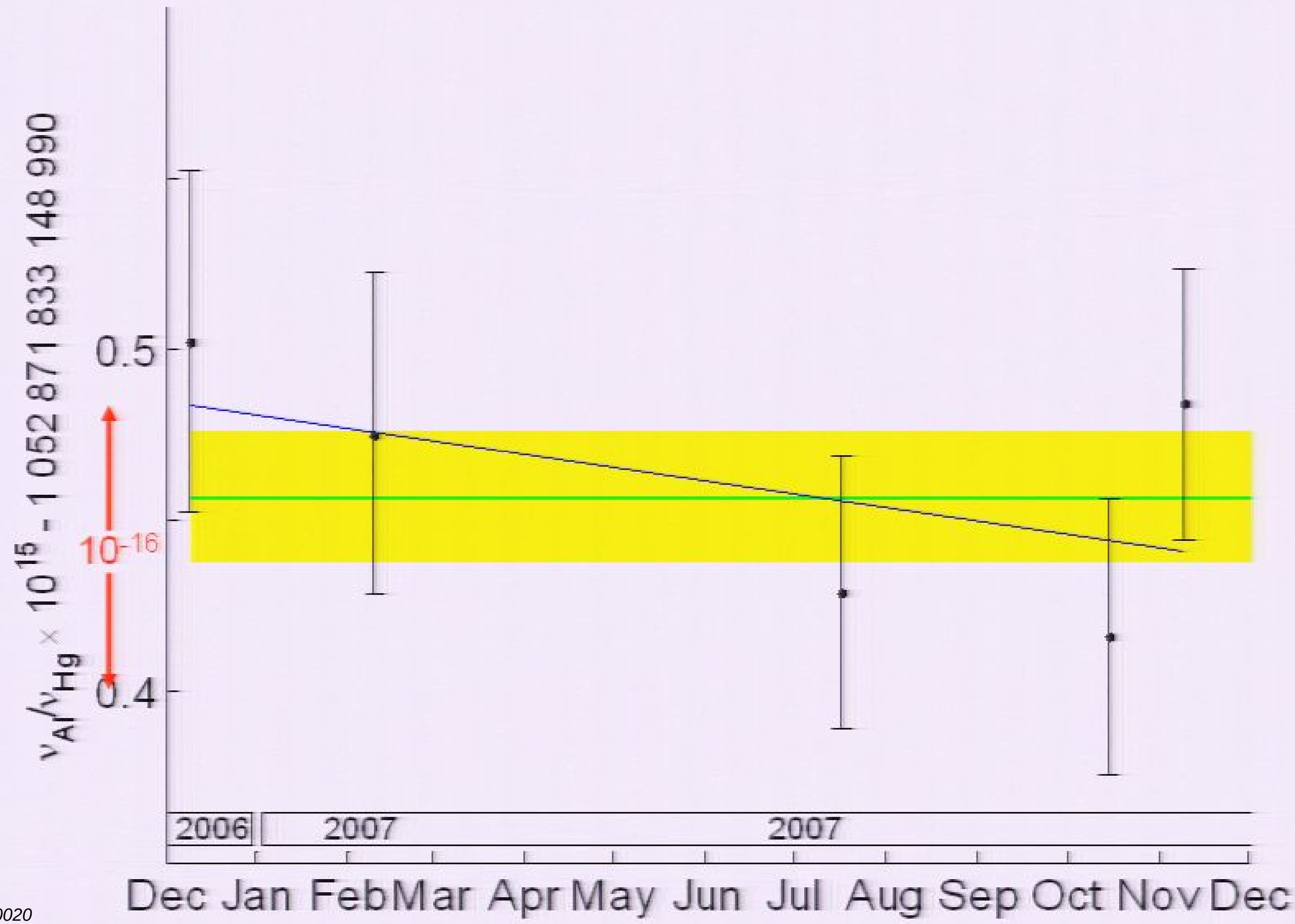
Al+/Hg+ Comparison

fs-comb locked to Hg+
measure beat with Al+

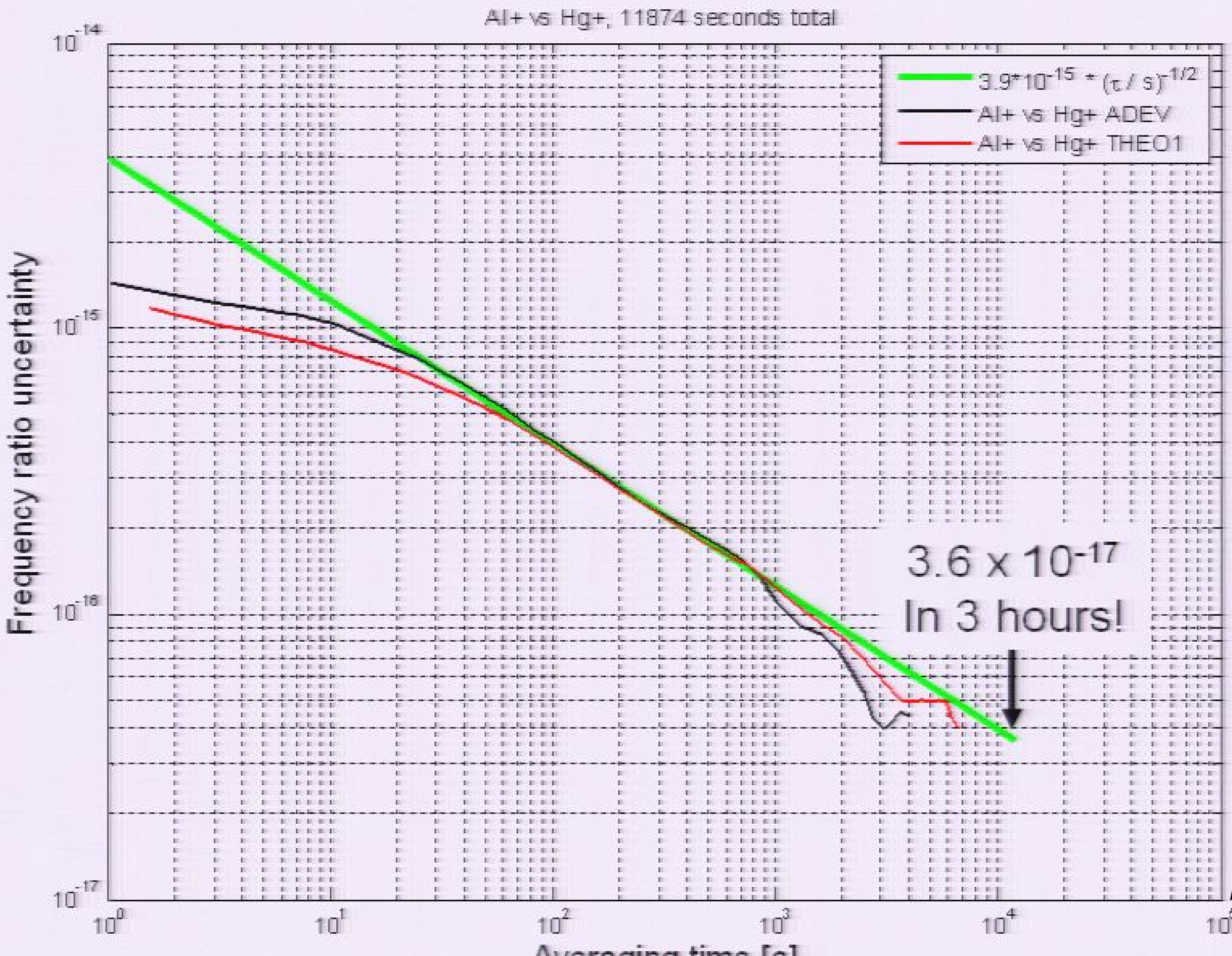


Al+/Hg+ Comparison

$\nu_{Al+}/\nu_{Hg+} = 1.052\ 871\ 833\ 148\ 990\ 438 \pm 55 \times 10^{-17}$



Al^+/Hg^+ Stability



$^{199}Hg^{+}$ error budget

Effect	Parameter	Shift [x 10^{-17}]	Uncertainty [x 10^{-17}]
Blackbody shift	Operating temperature	negligible	Negligible
Micromotion 2nd order Doppler	RF field	–0.3	0.3
Micromotion AC Stark	RF field	0.3	0.3
Secular 2nd order Doppler	Secular temperature	–0.3	0.3
2nd order Zeeman	magnetic field	–120.3	0.5
Servo Error	Loop gain	0	0.2
AC Zeeman	trap RMS field	0	1.0
Quadrupole Shift	Average on B field orientation	0	1.0
Background (He) gas collisions	Collision period	0	0.4
Total		–120.6	1.6

$^{199}Hg^{+}$ error budget

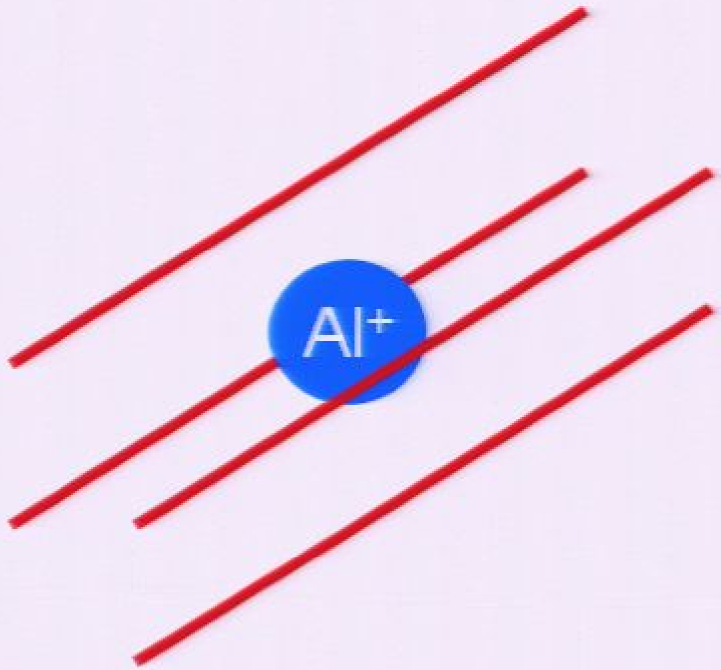
Effect	Parameter	Shift [x 10^{-17}]	Uncertainty [x 10^{-17}]
Blackbody shift	Operating temperature	negligible	Negligible
Micromotion 2nd order Doppler	RF field	–0.3	0.3
Micromotion AC Stark	RF field	0.3	0.3
Secular 2nd order Doppler	Secular temperature	–0.3	0.3
2nd order Zeeman	magnetic field	–120.3	0.5
Servo Error	Loop gain	0	0.2
AC Zeeman	trap RMS field	0	1.0
Quadrupole Shift	Average on B field orientation	0	1.0
Background (He) gas collisions	Collision period	0	0.4
Total		–120.6	1.6

Accurate evaluation with microwave spectoscopy

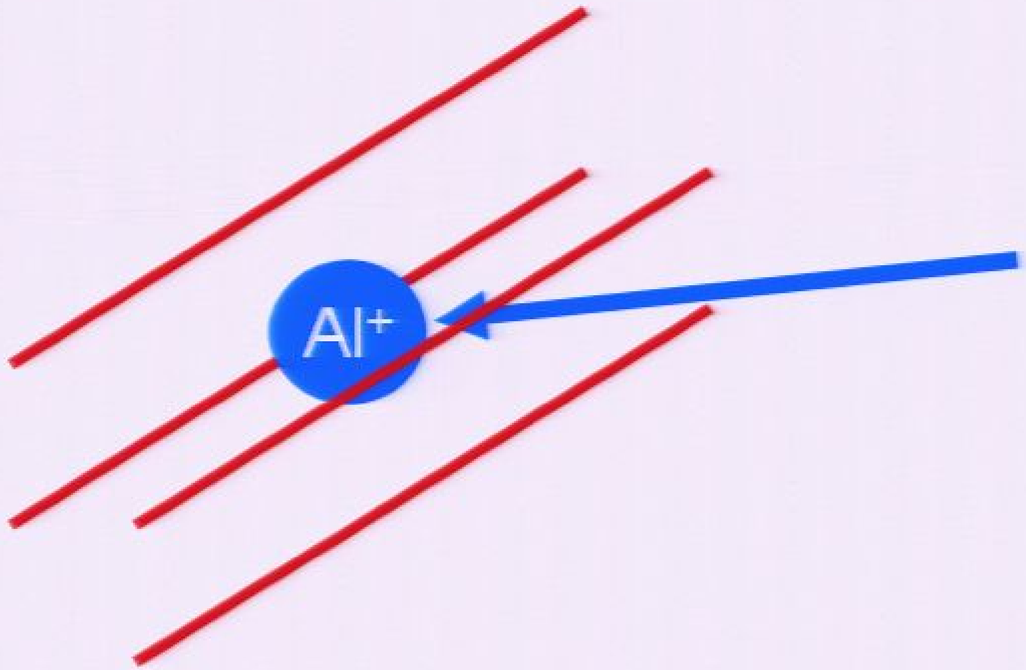
$^{27}Al^{+}$ error budget

Effect	Parameter	Shift [x 10 $^{-17}$]	Uncertainty [x 10 $^{-17}$]
Blackbody shift	Operating temperature	-1.2	0.5
Micromotion 2nd order Doppler	Axial RF field	-0.3	0.3
Micromotion 2nd order Doppler	Radial static field	-2	2
Secular 2nd order Doppler	Radial temperature	-1.1	0.8
2nd order Zeeman	RMS magnetic field	-68.5	0.1
Be^{+} cooling laser Stark shift	I / Isat	-0.7	0.3
1st-order Doppler from correlated ion movement		0	0.1
Total		**-73.5**	**2.2**

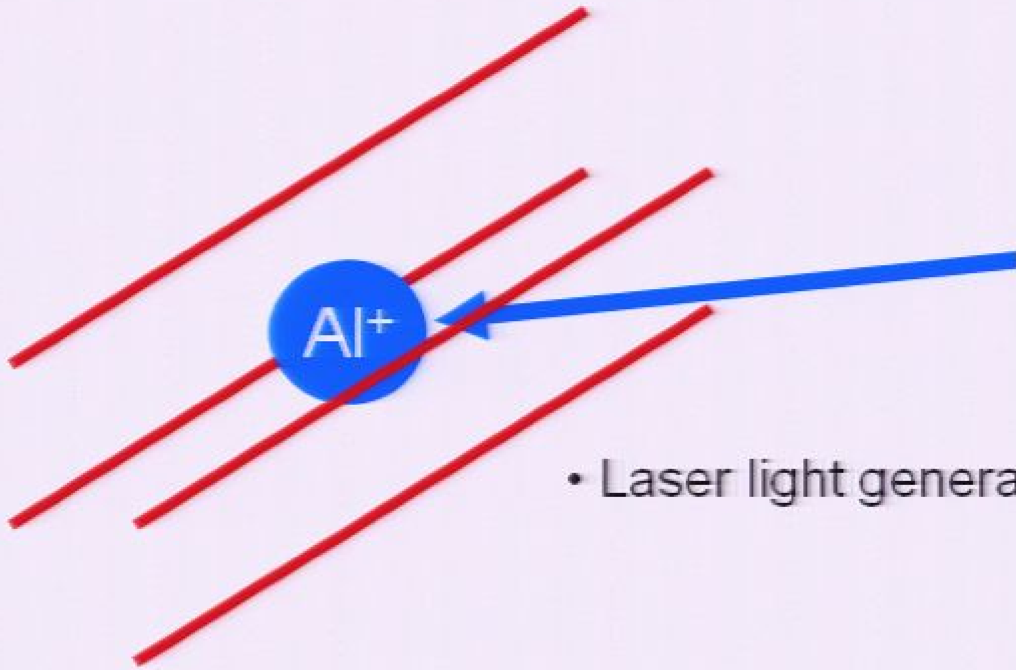
Correlated 1st-order Doppler shift



Correlated 1st-order Doppler shift

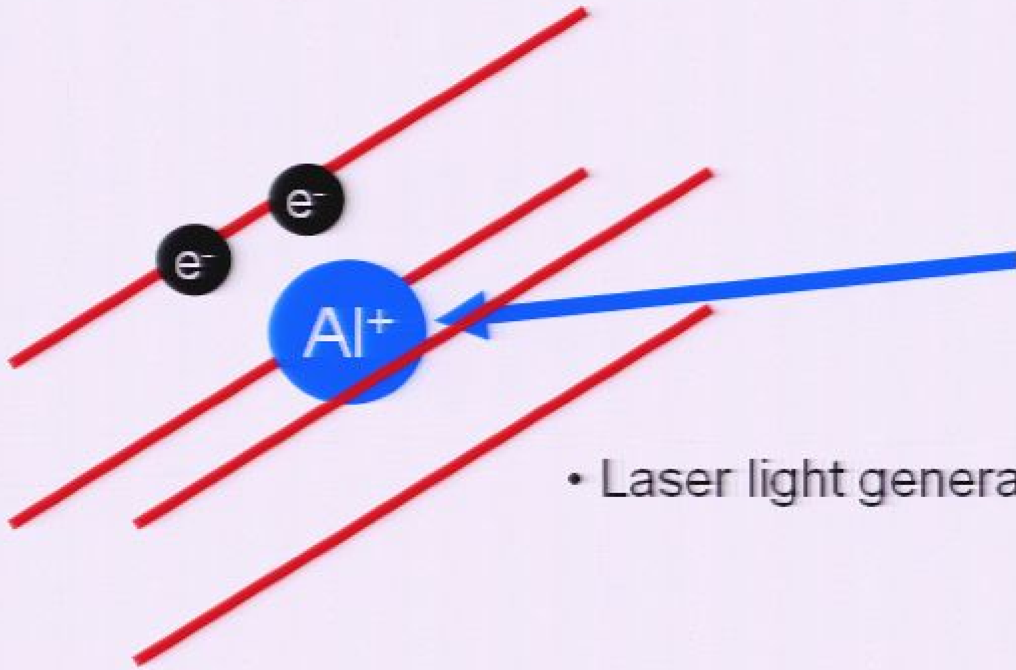


Correlated 1st-order Doppler shift



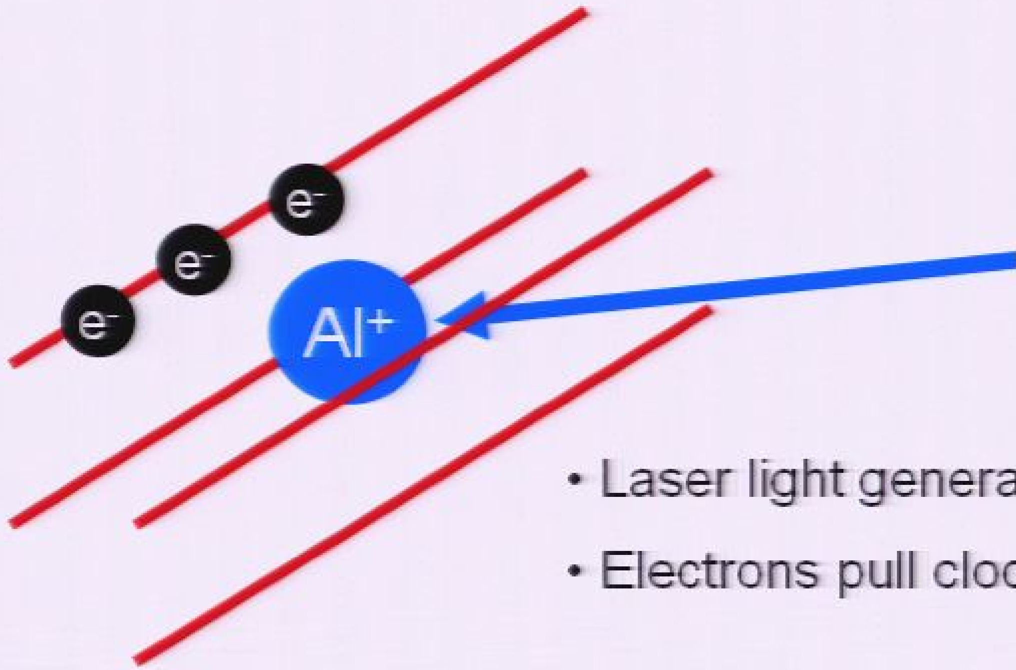
- Laser light generates photo-electrons

Correlated 1st-order Doppler shift



- Laser light generates photo-electrons

Correlated 1st-order Doppler shift



- Laser light generates photo-electrons
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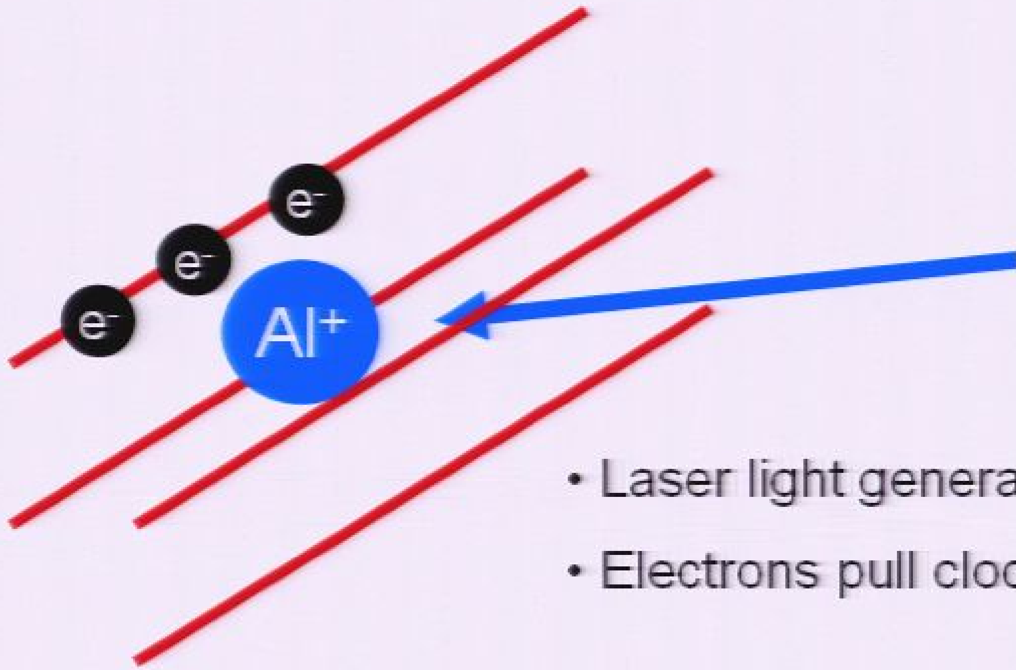
Correlated 1st-order Doppler shift



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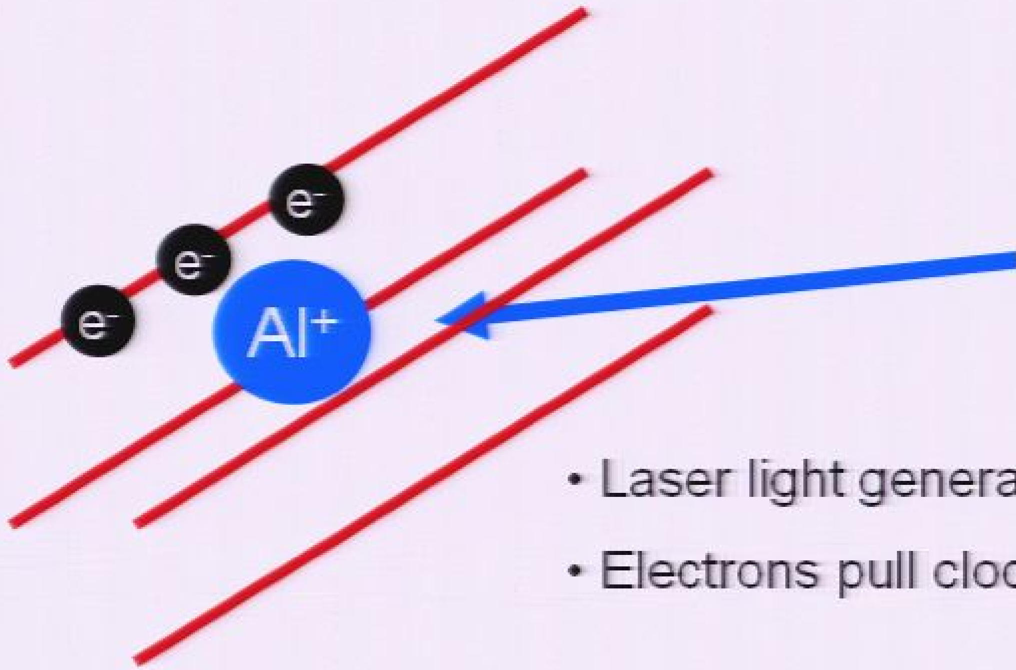

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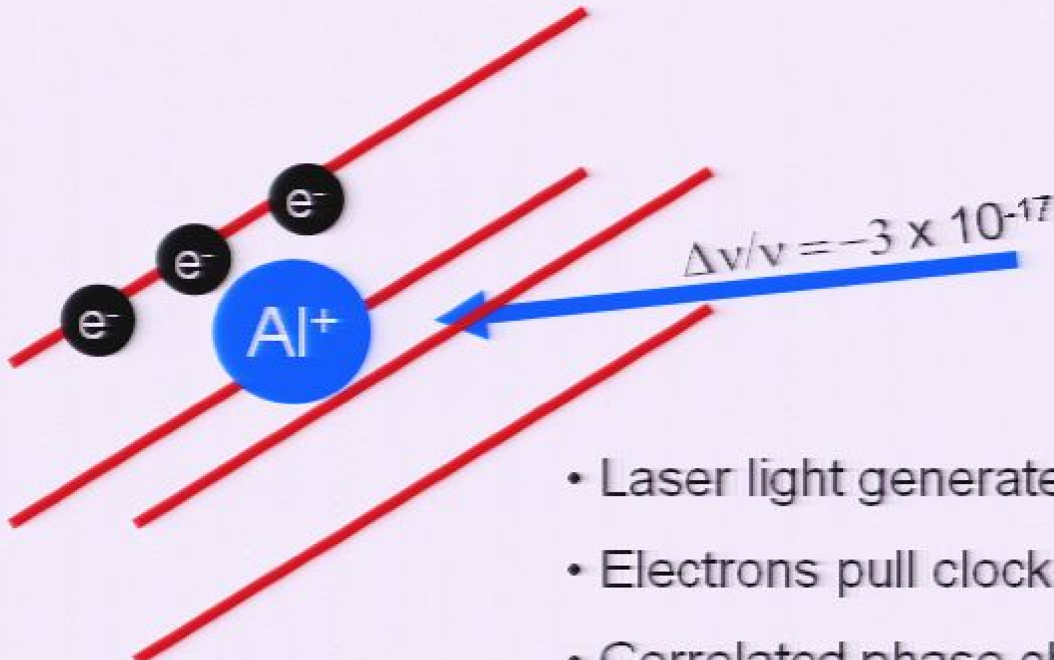
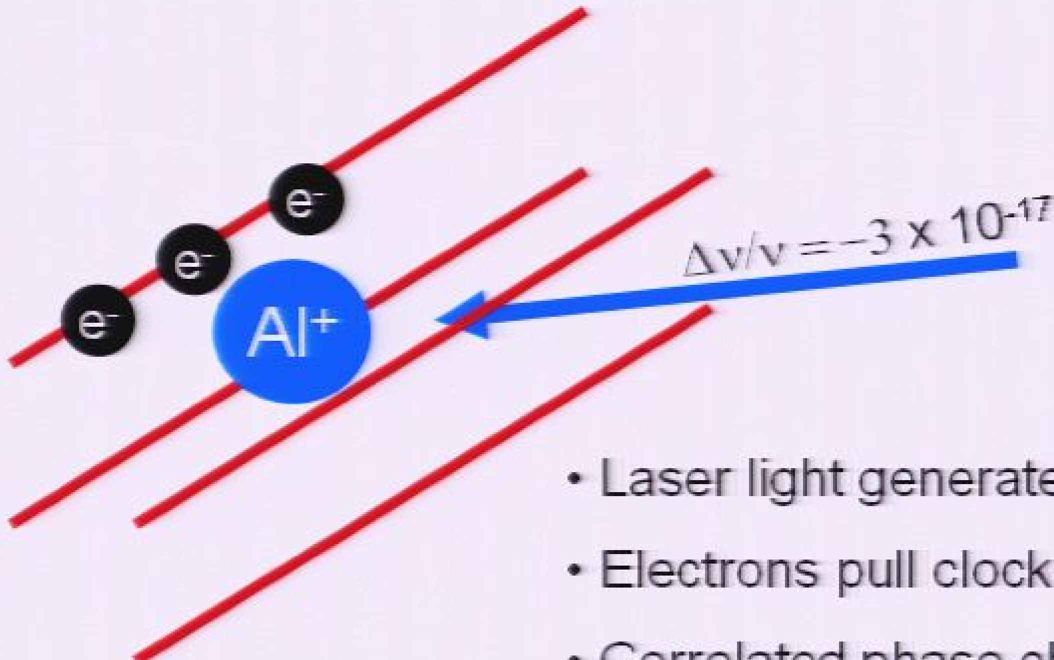


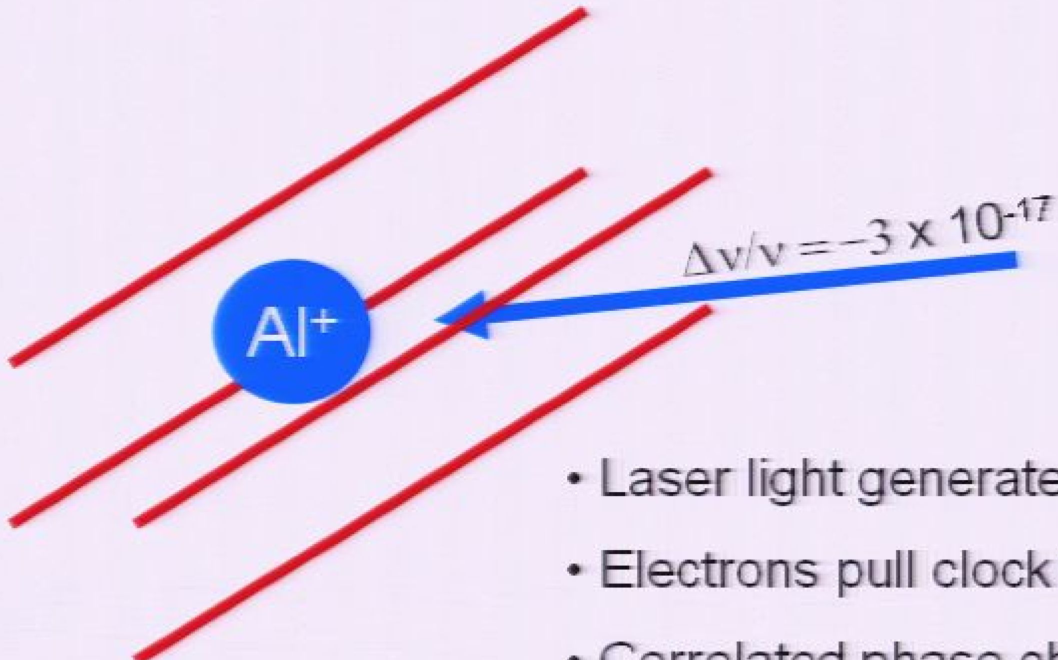
- Laser light generates photo-electrons
- Electrons pull clock ion
- Correlated phase chirp during each interrogation pulse

Correlated 1st-order Doppler shift



- Laser light generates photo-electrons
- Electrons pull clock ion
- Correlated phase chirp during each interrogation pulse
- Discharge after probe pulse

Correlated 1st-order Doppler shift



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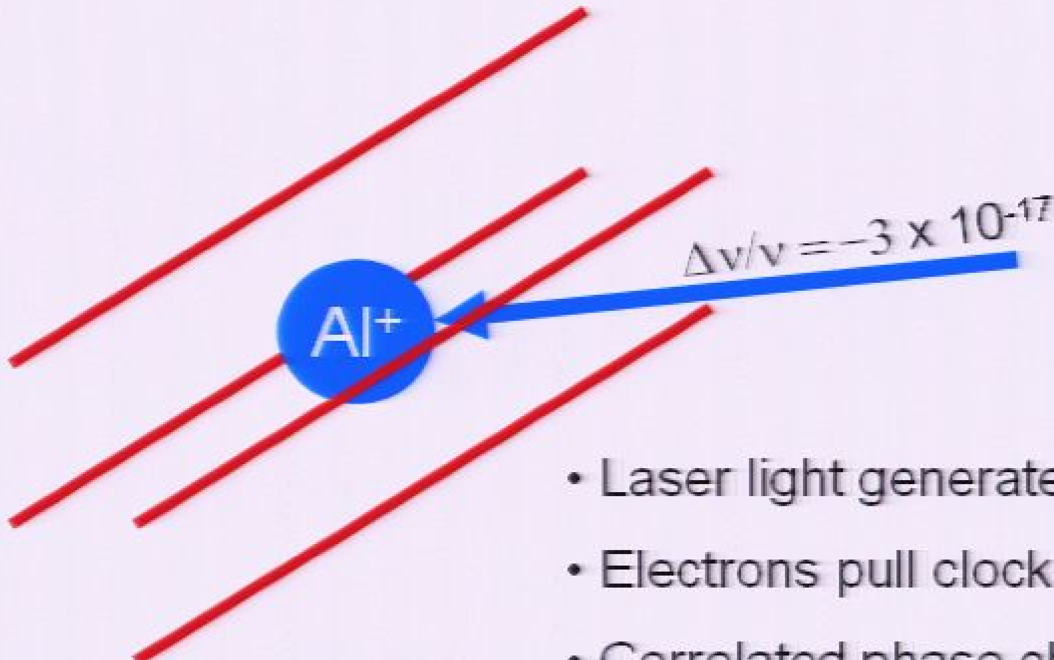
Correlated 1st-order Doppler shift



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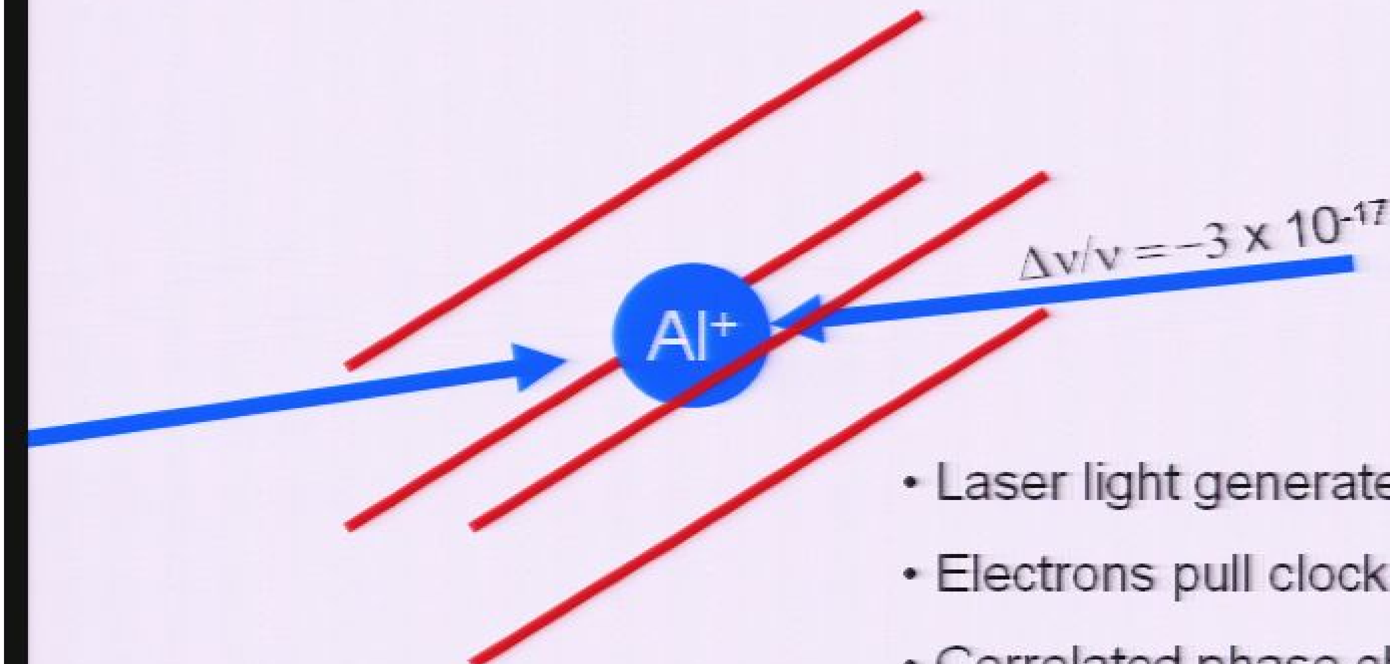
Correlated 1st-order Doppler shift



- Laser light generates photo-electrons
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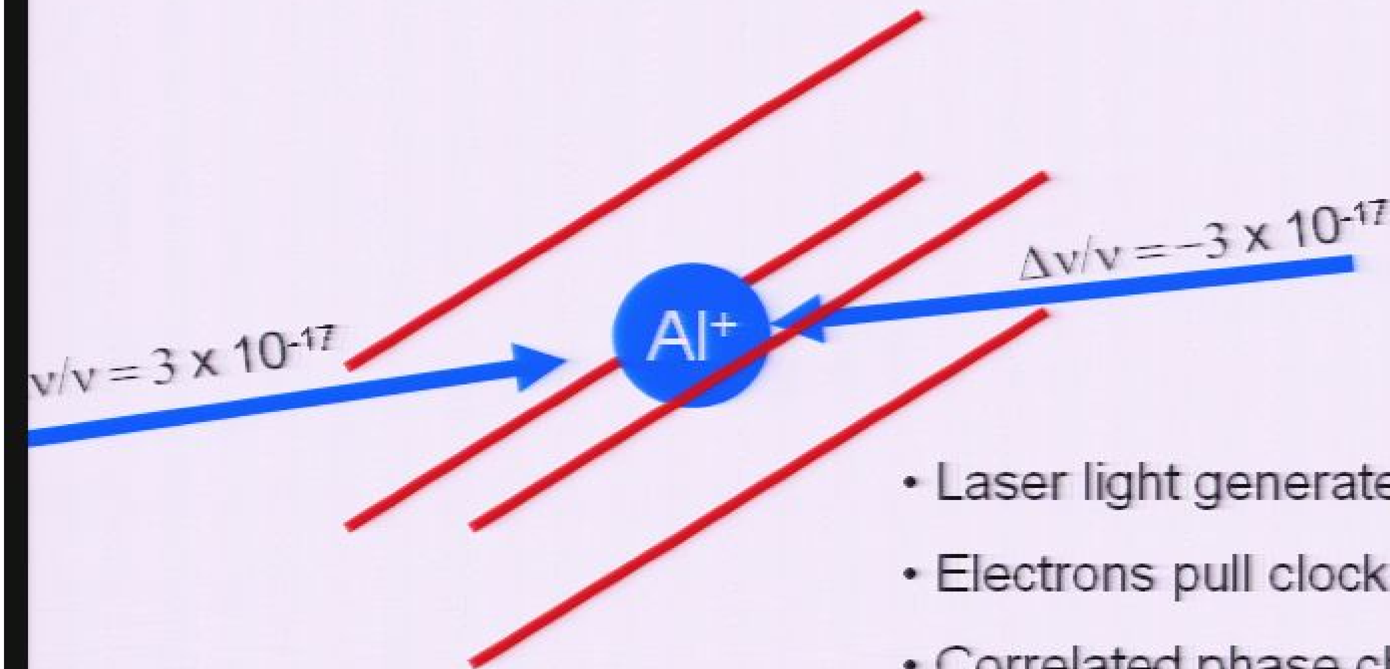
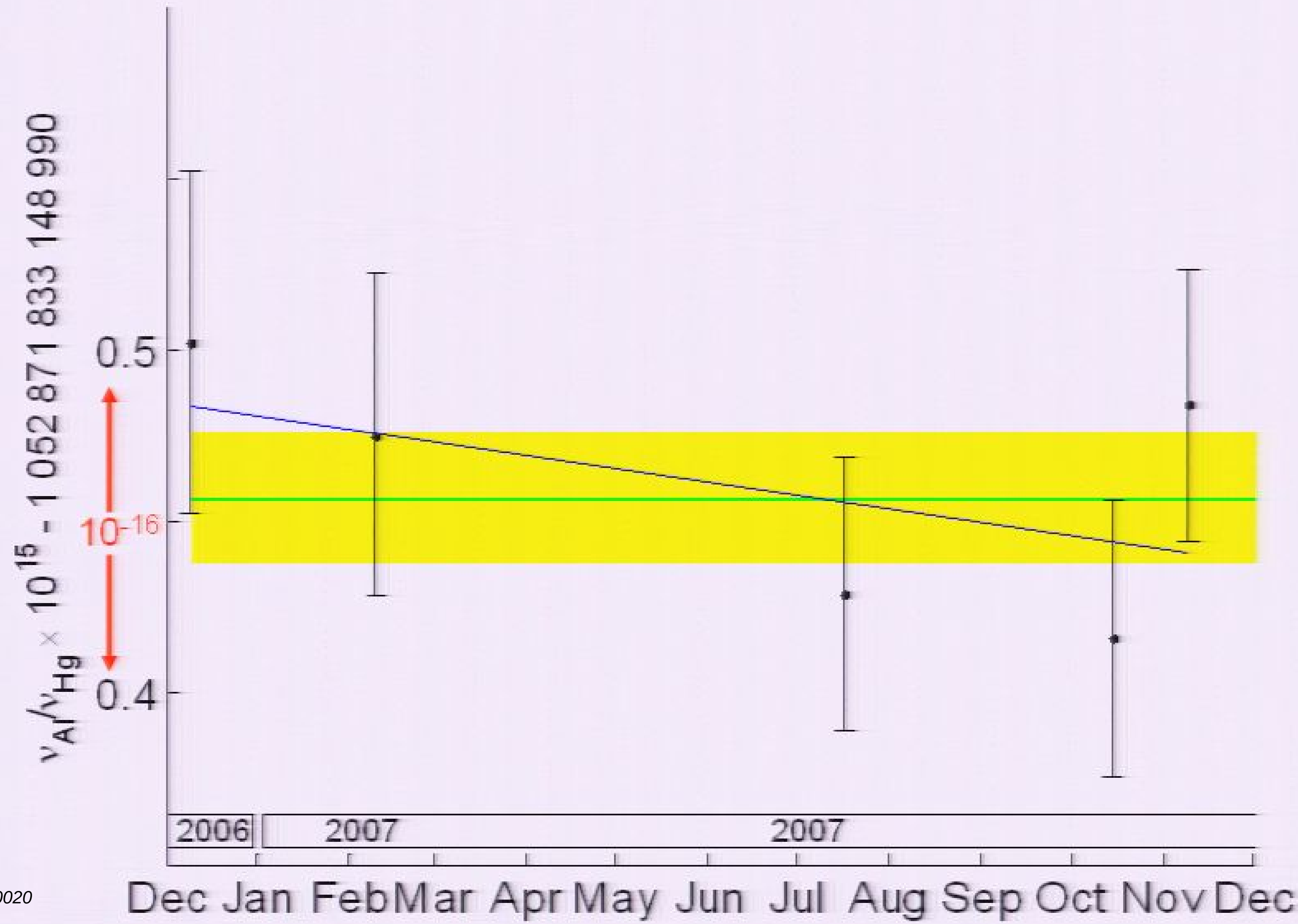
- Discharge after probe pulse
- Solution: probe from both directions to measure and constrain effect.

Correlated 1st-order Doppler shift

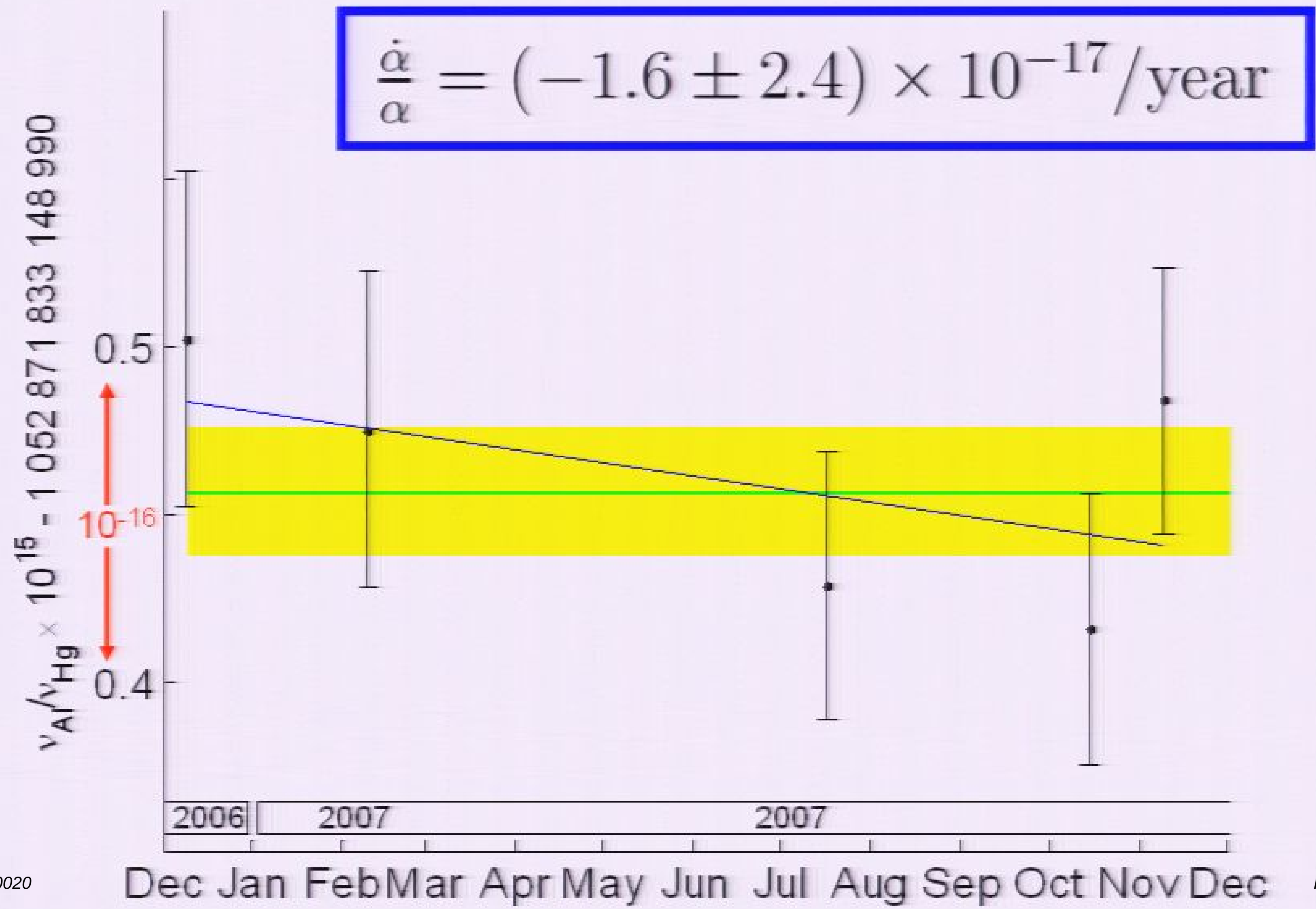


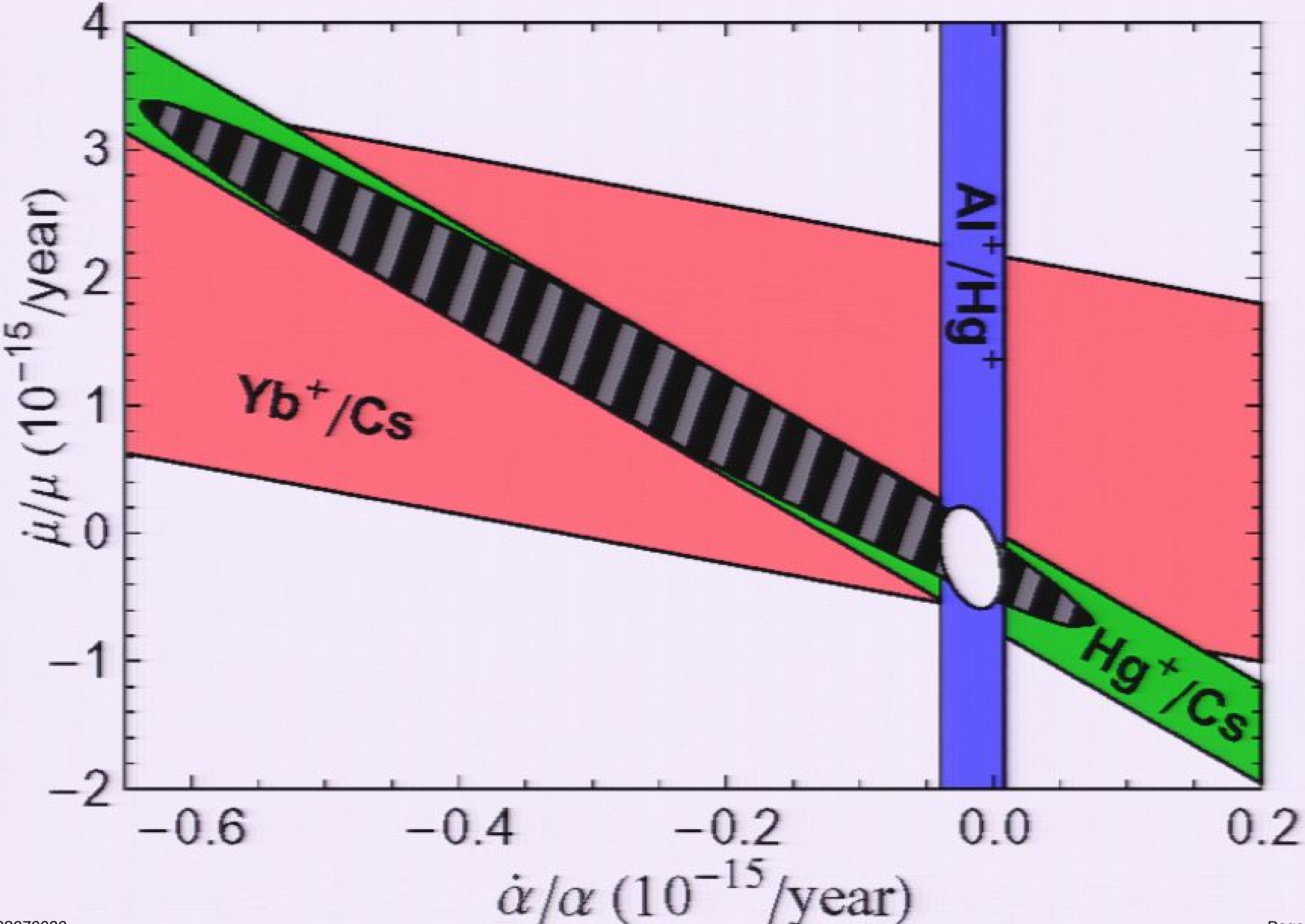
- Laser light generates photo-electrons
- Electrons pull clock ion
- Correlated phase chirp during each interrogation pulse
- Discharge after probe pulse
- Solution: probe from both directions to measure and constrain effect.
- Effect not noticeable in Al^+ measurements

Al+/Hg+ Comparison



Al+/Hg+ Comparison

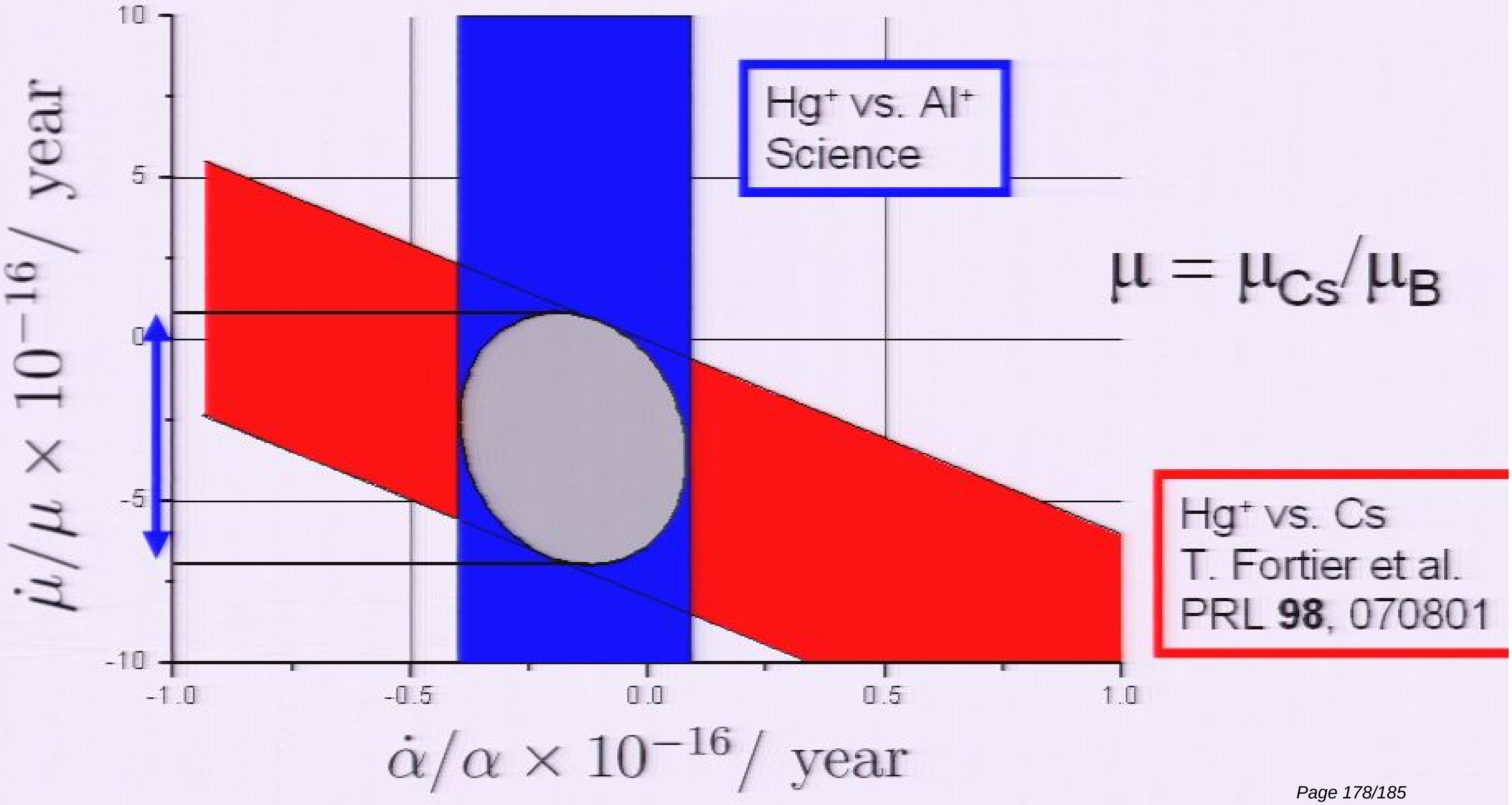




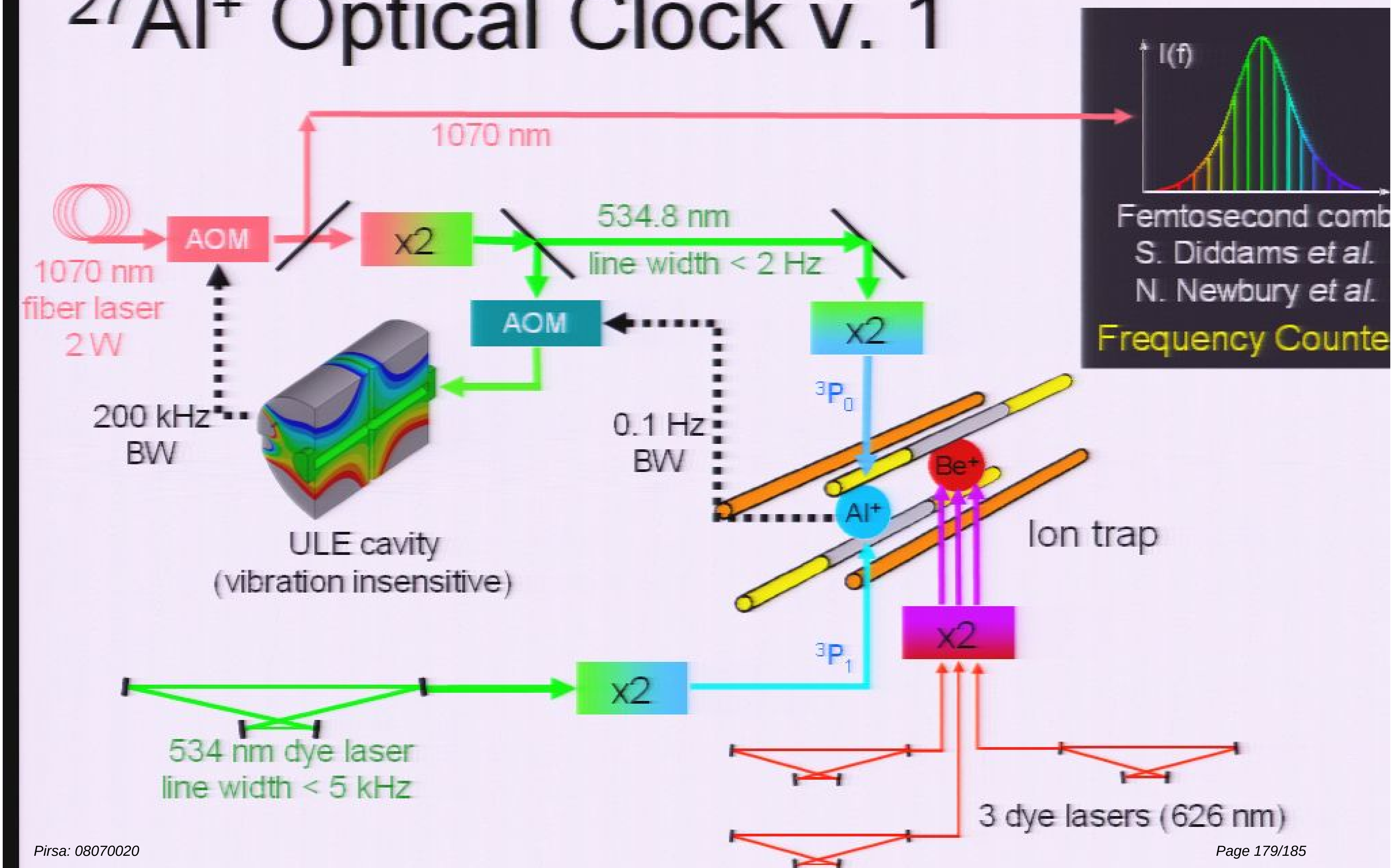
4
3
2
1
0
−1
−2
−0.6
−0.4
−0.2
0.0
0.2
μ̇/μ (10^−15/year)
α̇/α (10^−15/year)
Yb+/Cs
Al+/Hg+
Hg+/Cs

Constraint on μ_{Cs}/μ_B

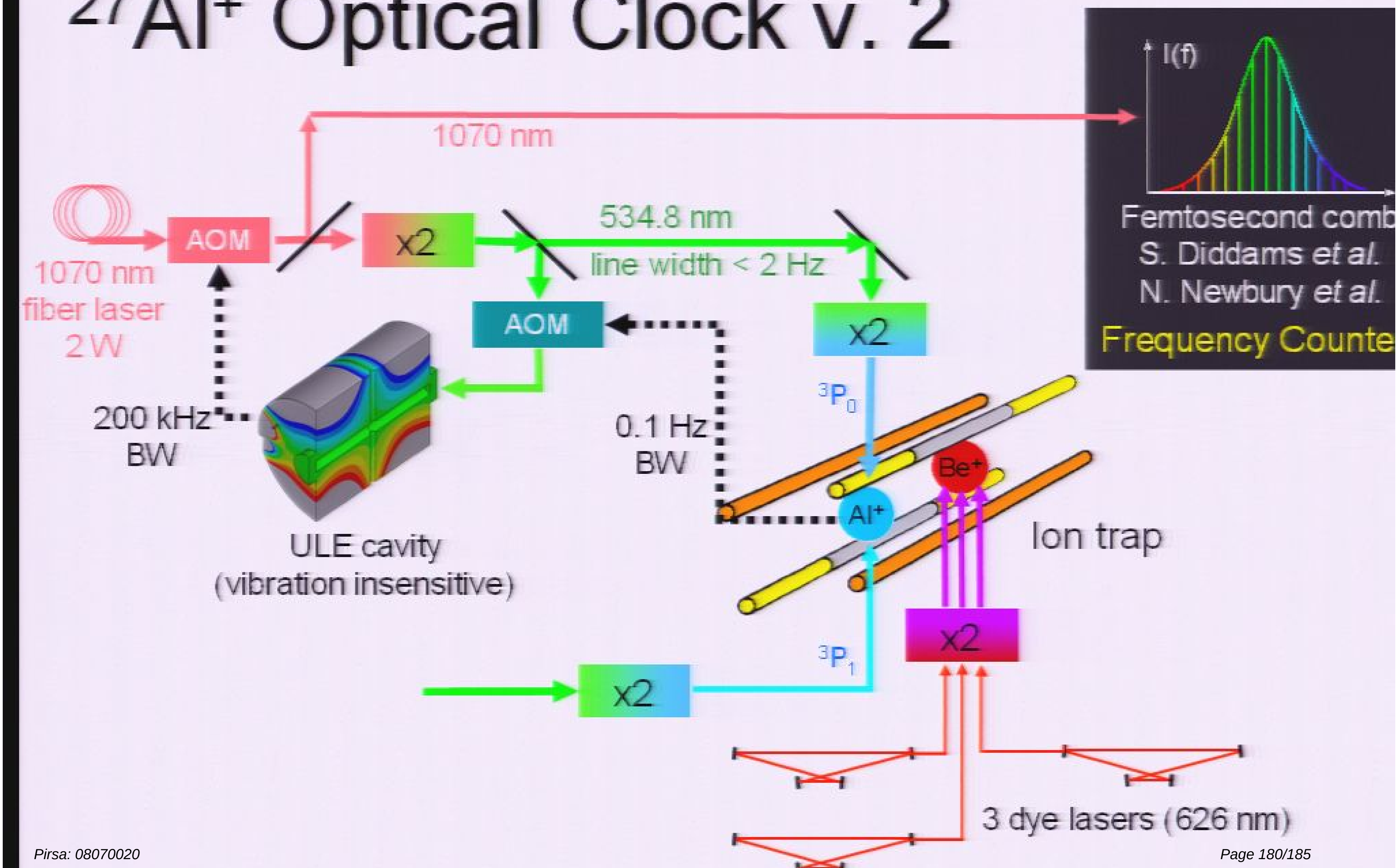
$\dot{\mu}/\mu \times 10^{-16} = (-3.1 \pm 3.9) \times 10^{-16}$ / year



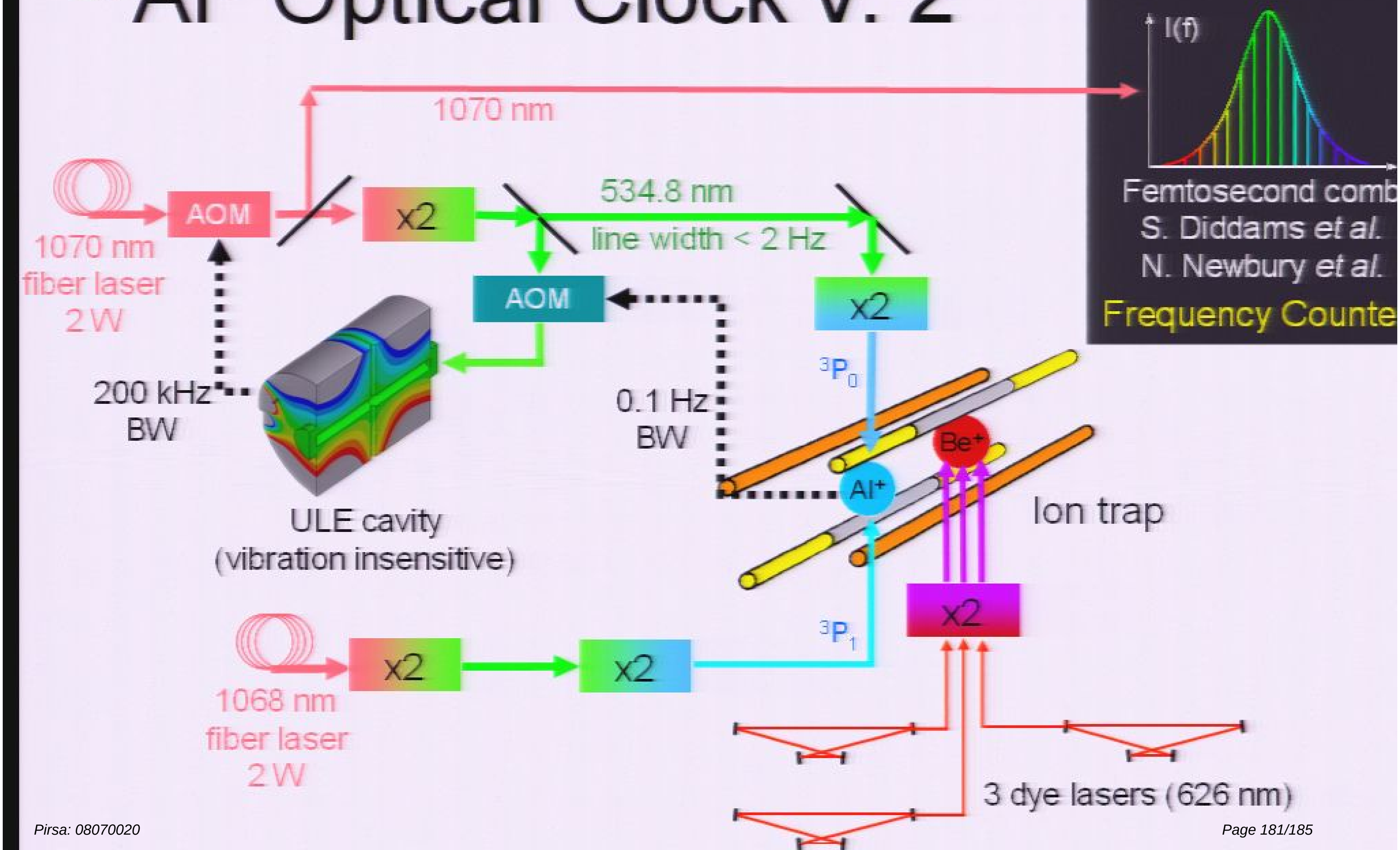
$^{27}Al^{+}$ Optical Clock v. 1



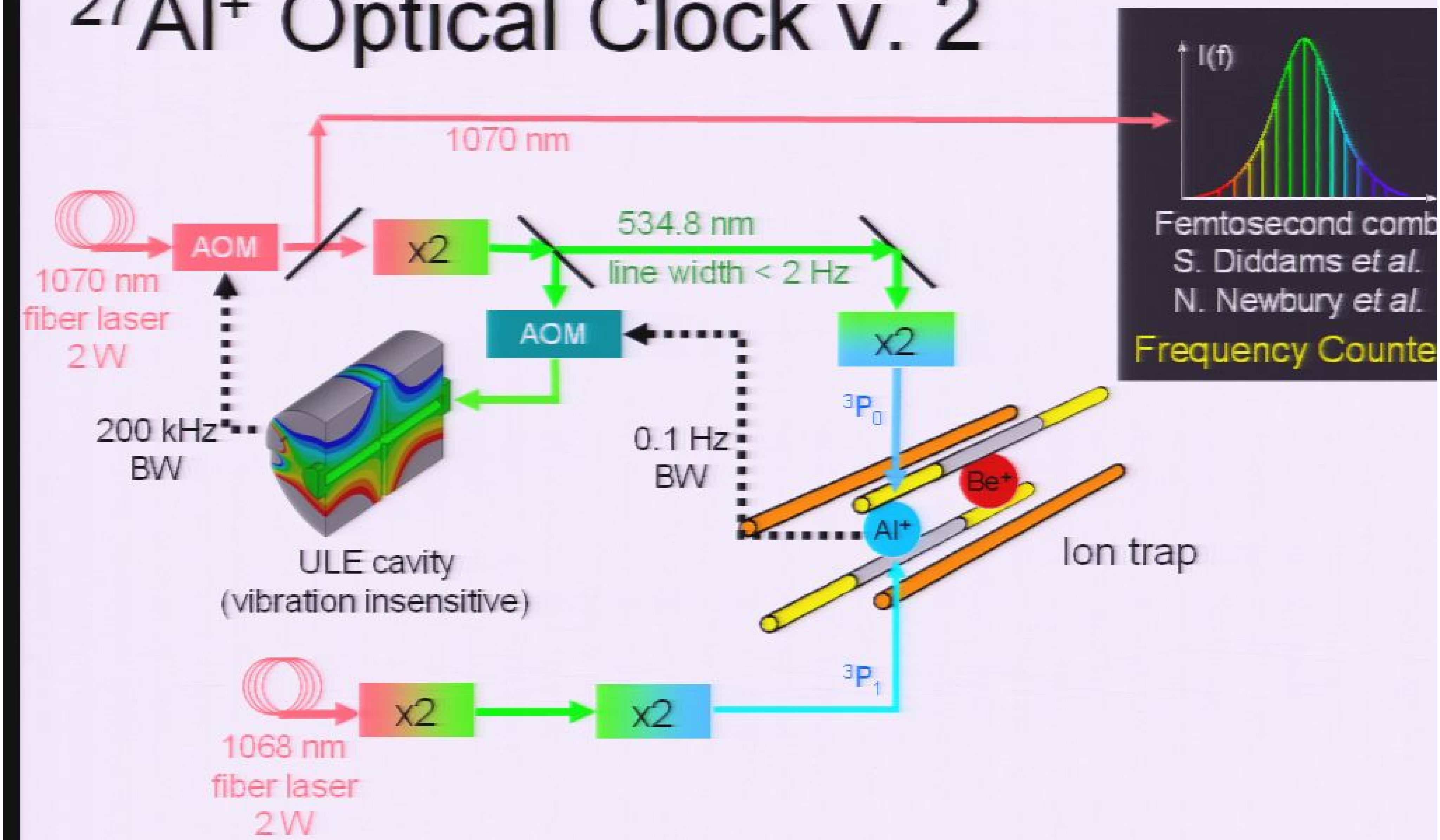
$^{27}Al^+$ Optical Clock v. 2



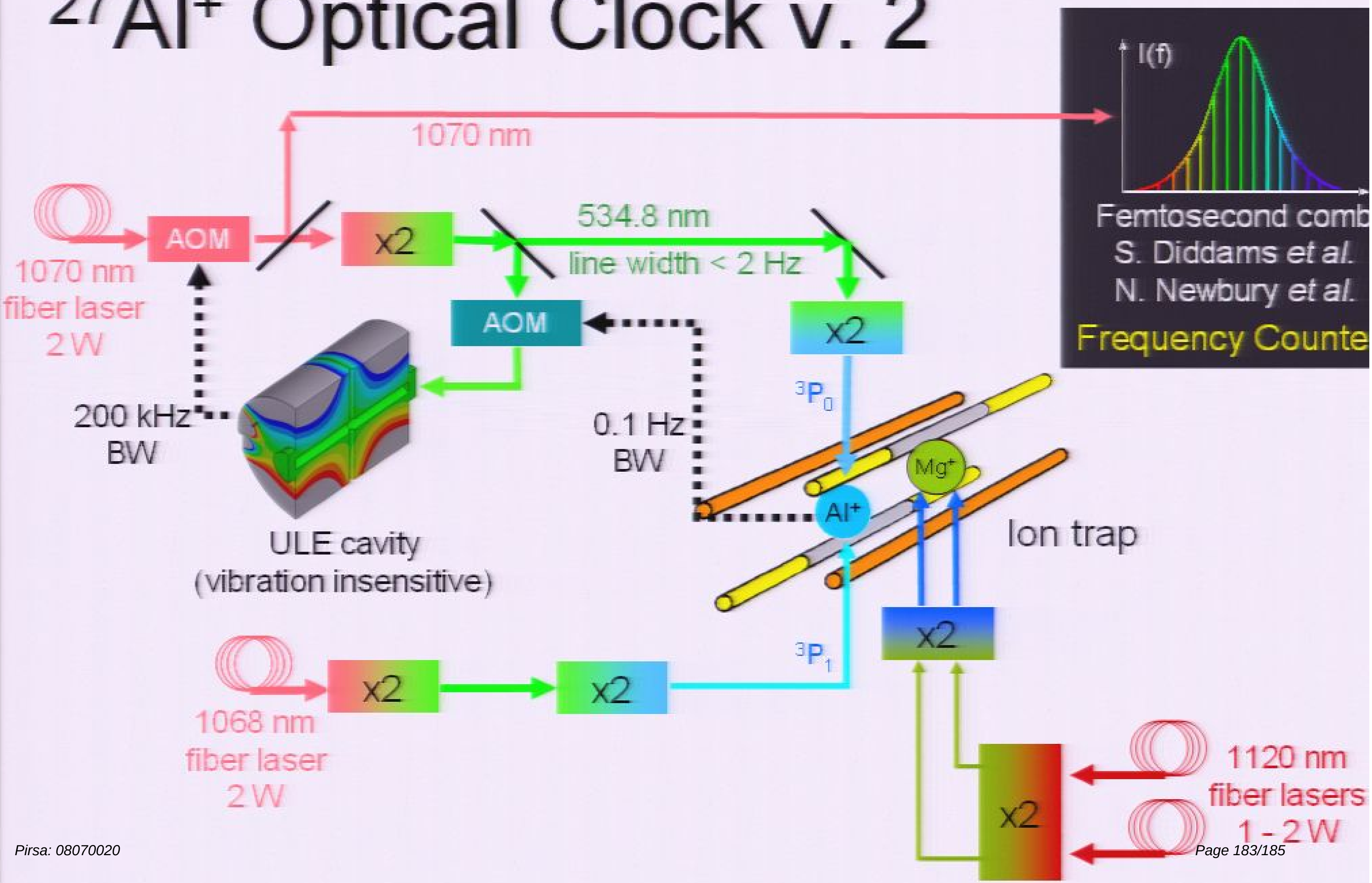
$^{27}Al^{+}$ Optical Clock v. 2



$^{27}Al^+$ Optical Clock v. 2

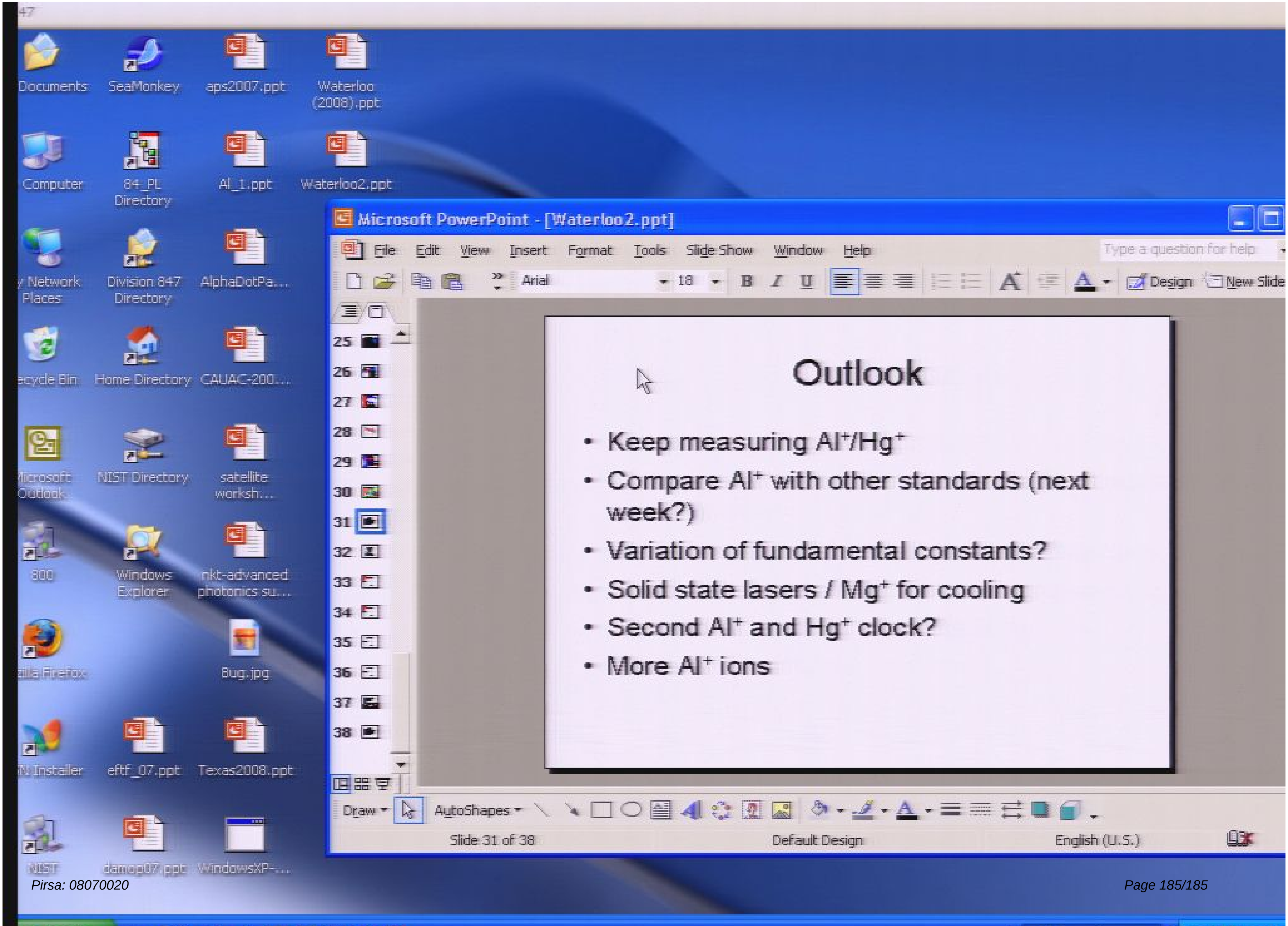


$^{27}Al^+$ Optical Clock v. 2



Outlook

- Keep measuring Al^+/Hg^+
- Compare Al^+ with other standards (next week?)
- Variation of fundamental constants?
- Solid state lasers / Mg^+ for cooling
- Second Al^+ and Hg^+ clock?
- More Al^+ ions


Microsoft PowerPoint - [Waterloo2.ppt]
Outlook
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• Variation of fundamental constants?
• Solid state lasers / Mg+ for cooling
• Second Al+ and Hg+ clock?
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Slide 31 of 38
Default Design
English (U.S.)