* Title credit goes to *Uncertain Principles* on *Science Blogs*.

Photons: Still Bosons*

Spectroscopic test of Bose-Einstein statistics for photons

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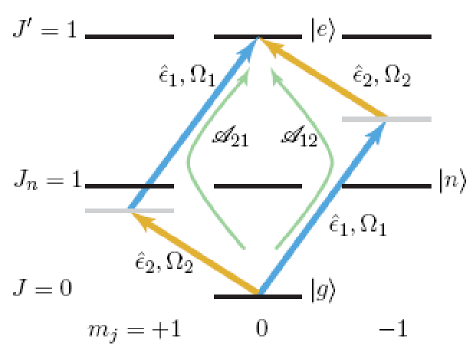
(Dated: February 4, 2010)

Using Bose-Einstein-statistics-forbidden two-photon excitation in atomic barium, we have limited the rate of statistics-violating transitions, as a fraction ν of an equivalent statistics-allowed transition rate, to $\nu < 4.0 \times 10^{-11}$ at the 90% confidence level. This is an improvement of more than three orders of magnitude over the best previous result. Additionally, hyperfine-interaction enabling of the forbidden transition has been observed, to our knowledge, for the first time.

PACS numbers: 42.50.Xa, 82.50.Pt



September 1st, 2010 Group meeting – Rockson Chang

Spin statistics theorem

- Relates the spin of a particle to the statistics it obeys.
- Integer spin particles (0,1,2…) == Bosons
  - WF symmetric under particle exchange

$$\phi(x)\phi(y) = \phi(y)\phi(x).$$

-- Obey Bose-Einstein statistics

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$$\phi(x)\phi(y) = -\phi(y)\phi(x)$$

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Why??...

- Feynman’s lectures on physics (Vol 3, Ch4 – Identical Particles)

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An explanation has been worked out by Pauli from complicated arguments of QFT and relativity… It appears to be one of the few places in physics where there is a rule which can be stated very simply, but for which no one has found a simple and easy explanation… This probably means that we do not have a complete understanding of the fundamental principle involved.

Spin statistics theorem

- A result from QFT
- Assumes:
  - Causality
  - Lorentz invariance in 3+1 spacetime dimensions
- Observing even a miniscule violation would rock the foundations of modern physics

- Quon algebra? $a_k a_l^\dagger - q a_l^\dagger a_k = \delta_{kl}$,
- Excitation in higher dimensions (string theory)?

Landau-Yang theorem

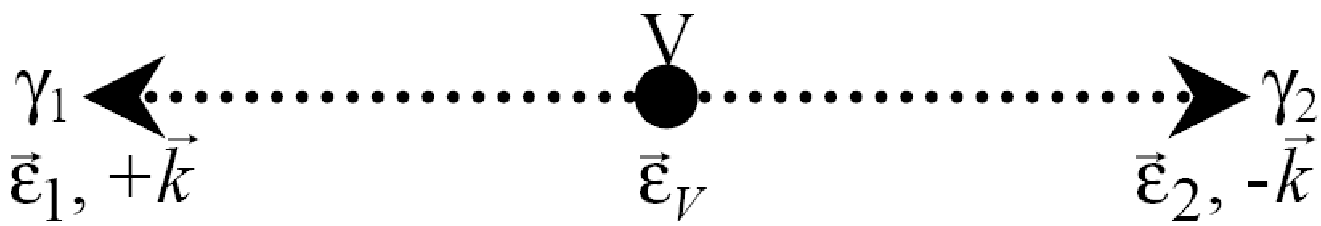

FIGURE 1. Kinematics of the decay $V \rightarrow \gamma\gamma$, in the rest frame of V.

- A neutral J=1 boson can't decay into two *degenerate* photons.
  - Resulting 2 photon state must have J'=1

$$\psi = |\uparrow\downarrow\rangle - |\uparrow\downarrow\rangle$$

- Ψ (J'=1) anti-symmetric under particle exchange

Spectroscopic test of Bose-Einstein statistics for photons

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- Turn this into a table-top atomic physics experiment by considering the time-reversed scenario:

Look for two photon absorption in Barium-138 (I=0)

J=0 + 2 γ → J'=1

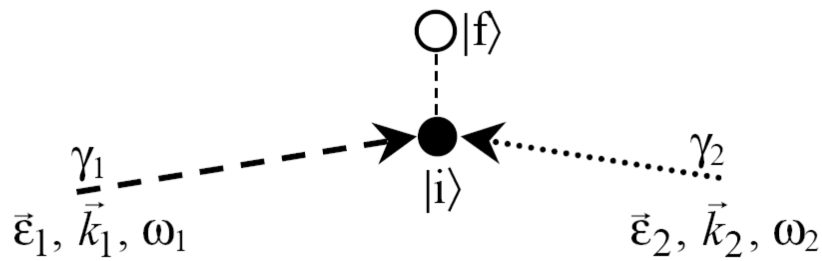
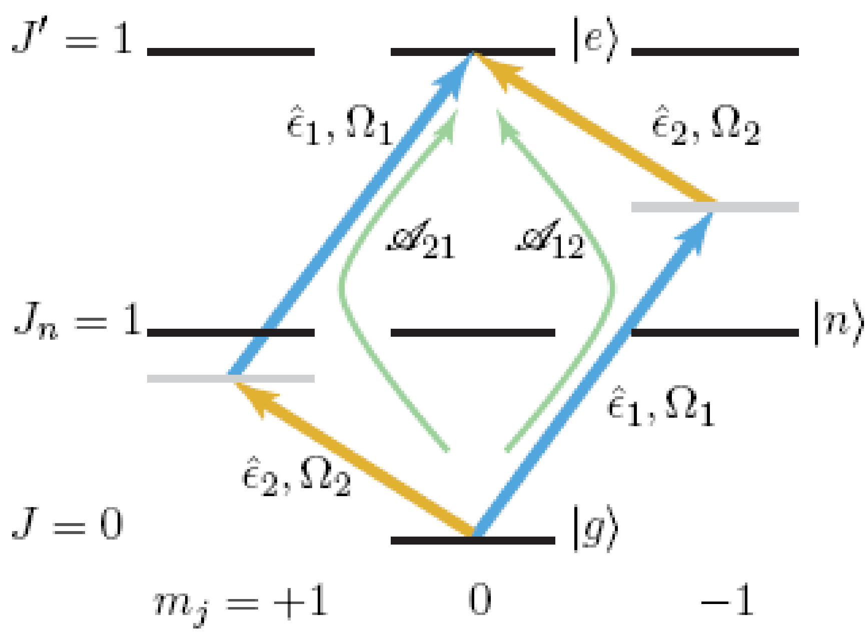


FIGURE 2. Kinematics of an atomic two-photon transition.



Orthogonal circular polarizations

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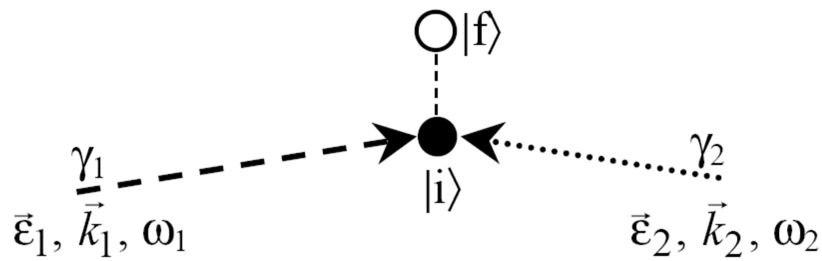

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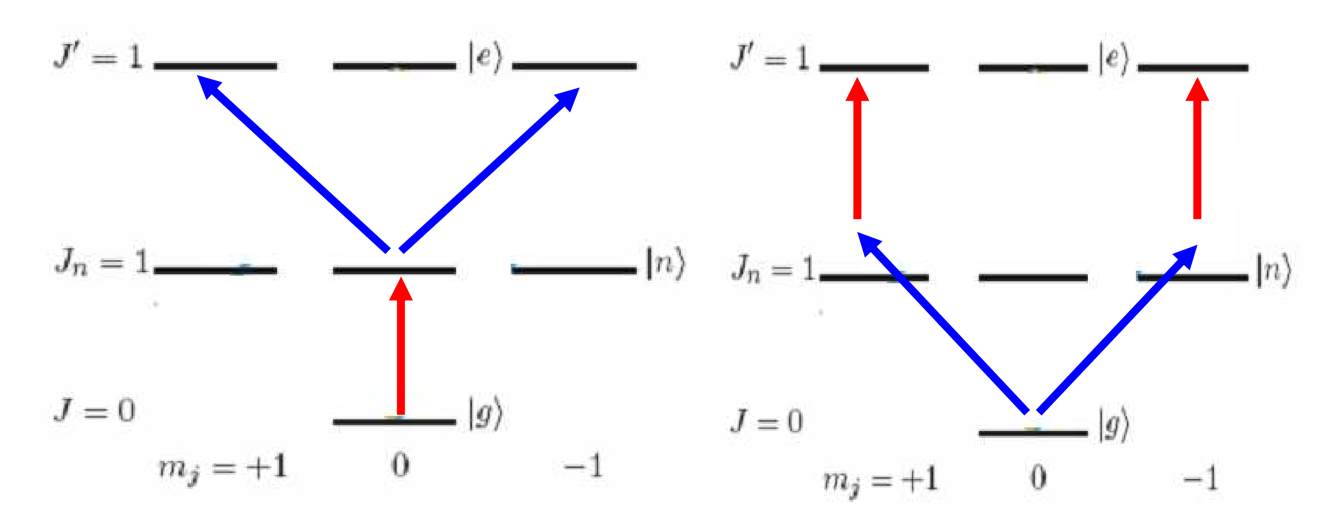

Orthogonal linear polarizations

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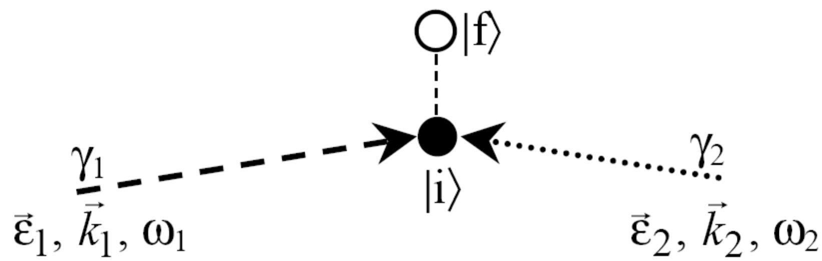

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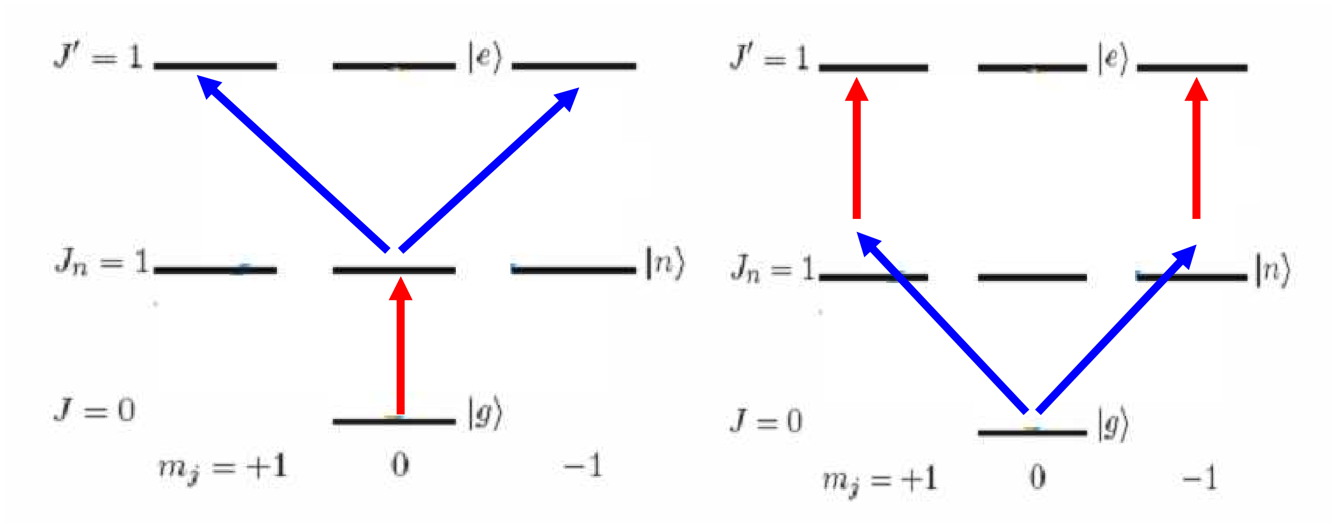


Orthogonal linear polarizations

Q1A: Pathways indistinguishable! (what about photons?)

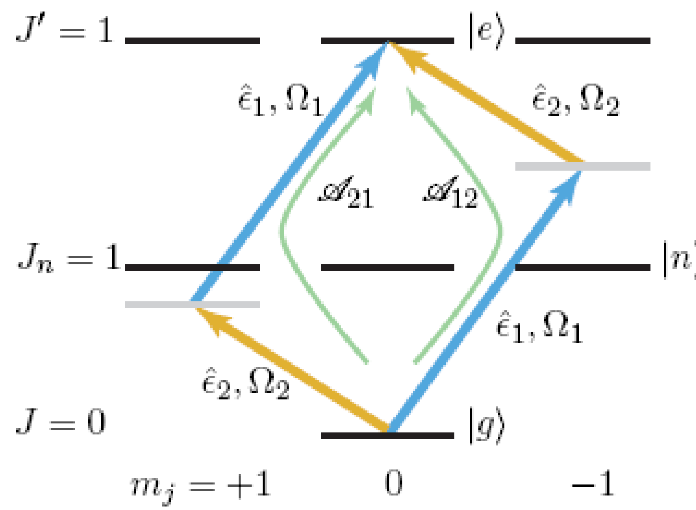
- Consider TPA rate

  (2nd order time-dependent perturbation, Fermi's golden rule)

$$W_{+} = \frac{2\pi}{\hbar^4} \times \left| \sum_n \mathscr{A}_{12}^{(n)} + \mathscr{A}_{21}^{(n)} \right|^2 \times \frac{1}{\pi} \frac{\Gamma/2}{(\Omega_1 + \Omega_2 - \omega_{eg})^2 + (\Gamma/2)^2} \frac{\bar{I}_1 \bar{I}_2}{4\epsilon_0^2 c^2},$$

$$\mathscr{A}_{jk}^{(n)} = \frac{\langle e| \hat{\epsilon}_k \cdot \mathscr{D} |n\rangle \langle n| \hat{\epsilon}_j \cdot \mathscr{D} |g\rangle}{\omega_{ng} - \Omega_j + i\Gamma_n/2}$$

- Generalize to allow for Bose-Einstein statistics violation
- Sum over intermediate states |n>
- Amplitudes for each path interfere



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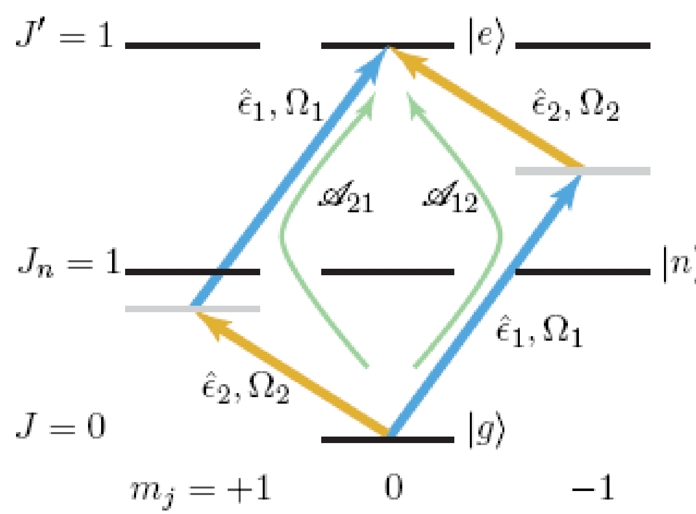

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$$W_{\pm} = \frac{2\pi}{\hbar^4} \times \left| \sum_n \mathscr{A}_{12}^{(n)} \pm \mathscr{A}_{21}^{(n)} \right|^2 \times \frac{1}{\pi} \frac{\Gamma/2}{(\Omega_1 + \Omega_2 - \omega_{eg})^2 + (\Gamma/2)^2} \frac{\bar{I}_1 \bar{I}_2}{4\epsilon_0^2 c^2},$$

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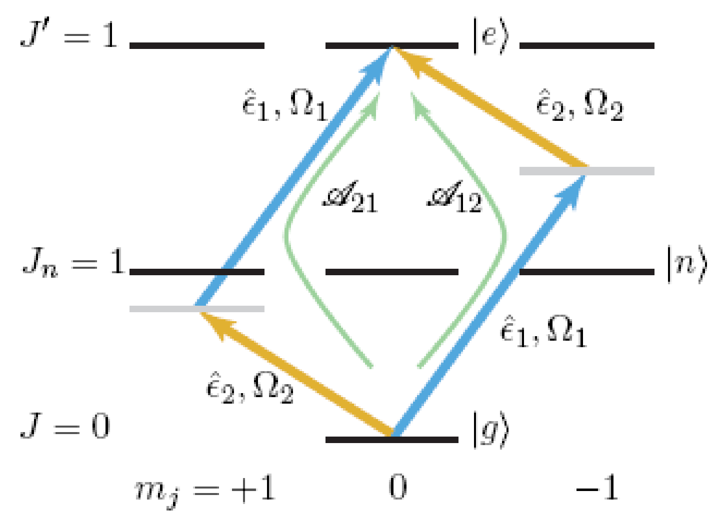
- Generalize to allow for Bose-Einstein statistics violation
- Sum over intermediate states |n>
- Amplitudes for each path interfere
  - Constructively, ψ (2 γ) symmetric
  - Destructively, ψ (2 γ) anti-symmetric

    (under *particle exchange*)



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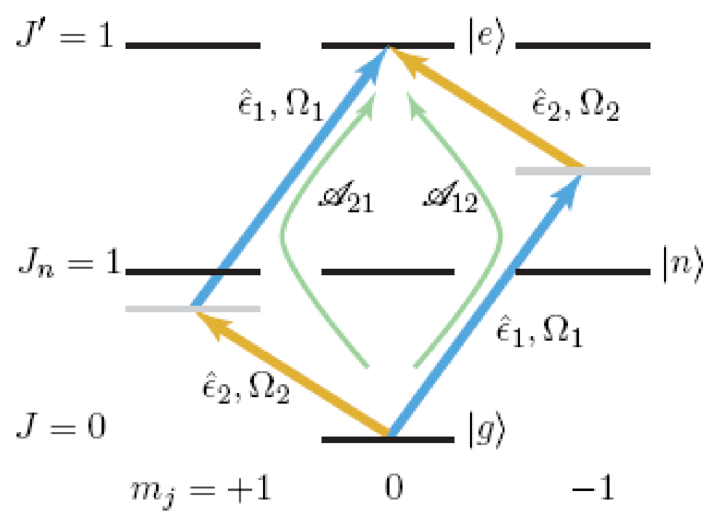
Q1B:

What determines the relative phase between paths? Is this equation valid for all 3 cases of photon states?

3 cases: distinguishable

indistinguishable symm / antisymm

Or am I thinking about this wrong?



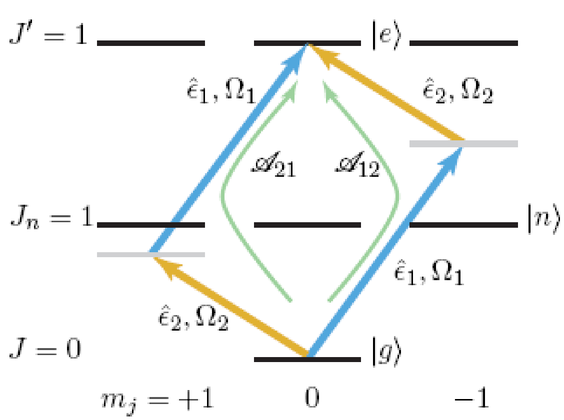
- Sum over intermediate levels, apply Wigner-Eckart theorem extracting the rank-1 irreducible component of the transition operator, and assume orthogonal light polarizations

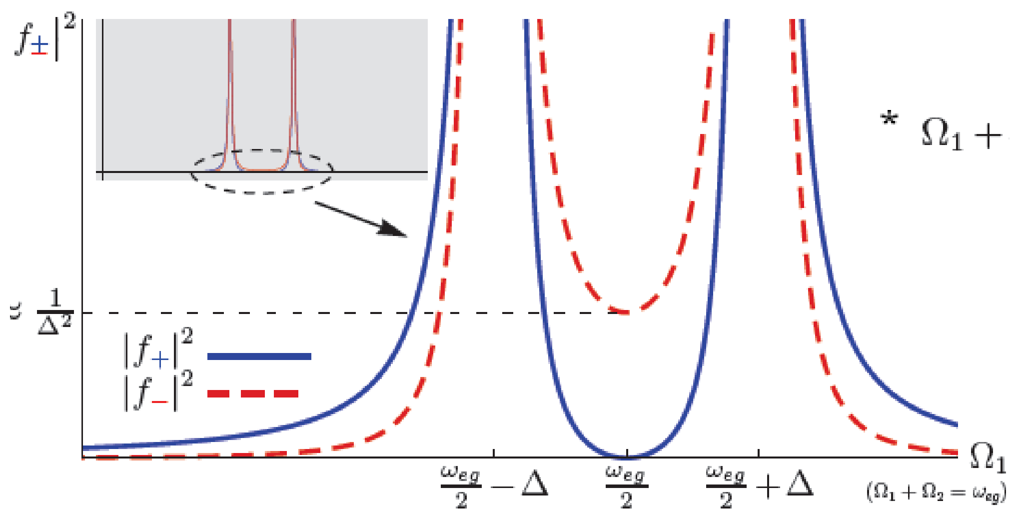
$$W_{\pm} = \left| f_{\pm} \right|^2 \frac{\Gamma/2}{\left(\Omega_1+\Omega_2-\omega_{eg}\right)^2+\left(\Gamma/2\right)^2} \frac{\mathcal{D}_{en}^2 \mathcal{D}_{ng}^2 \bar{I}_1 \bar{I}_2}{3\epsilon_0^2 c^2 \hbar^4},$$

$$f_{+} = \frac{\left(\Omega_1-\Omega_2\right)/2}{\left(\omega_{ng}-\Omega_1+i\Gamma_n/2\right)\left(\omega_{ng}-\Omega_2+i\Gamma_n/2\right)},$$

$$f_{-} = \frac{\omega_{ng}-\left(\Omega_1+\Omega_2\right)/2+i\Gamma_n/2}{\left(\omega_{ng}-\Omega_1+i\Gamma_n/2\right)\left(\omega_{ng}-\Omega_2+i\Gamma_n/2\right)},$$

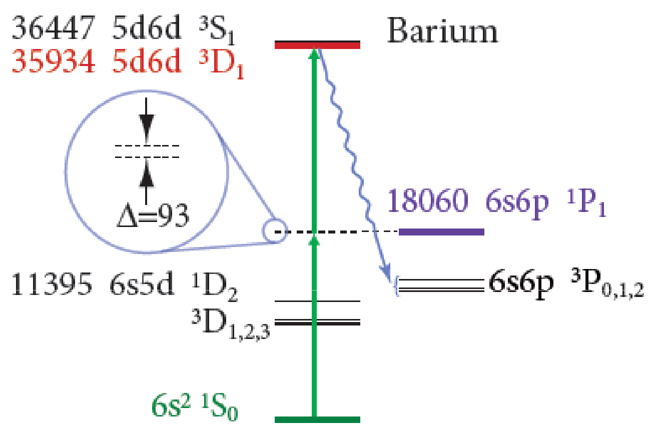
Q2: What symmetry is leading to this selection rule for the symmetric state?



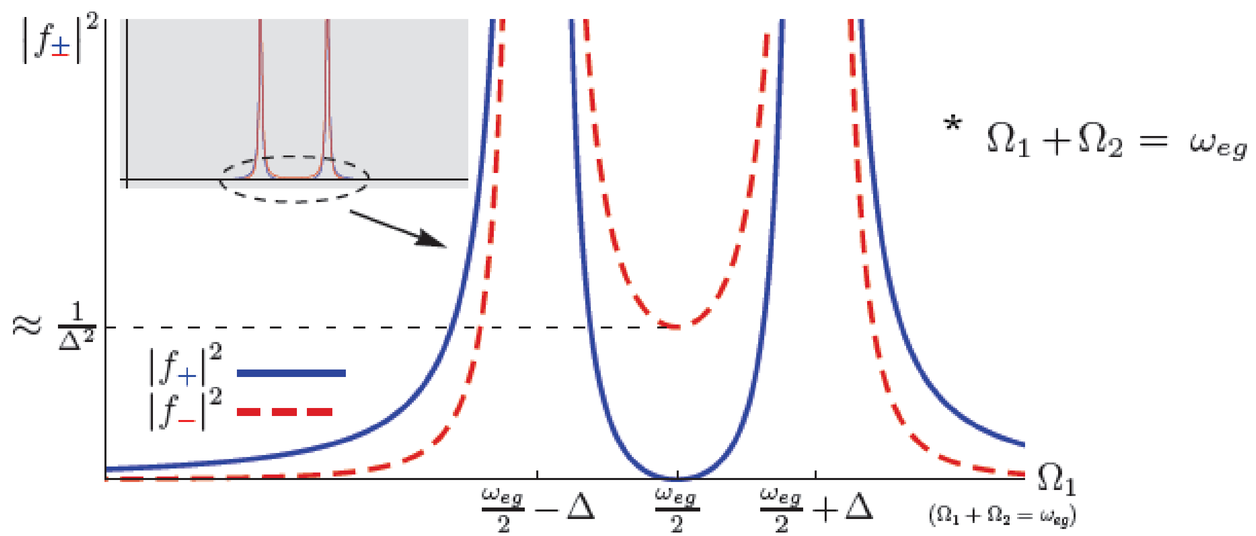


* $\Omega_1 + \Omega_2 = \omega_{eg}$

- When photons are degenerate $\Omega_1=\Omega_2=\omega_{eg}/2$
  - W+=0, exchange-symmetric photon state can not excite transition by TPA selection rules
  - W-≈1/Δ2, exchange-antisymmetric photon state allowed if we ignore SST

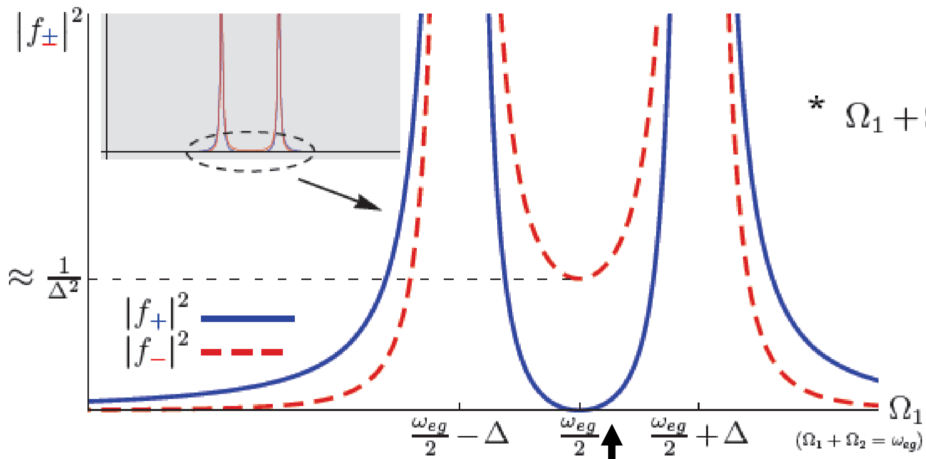


1 cm^{-1} ≈ 30 GHz



- Measured fluorescence signal:

$$\mathcal{S}(\delta) = \gamma \left\{ W_{+}(\delta) + \nu W_{-}(\delta) \right\}$$



* $\Omega_1 + \Omega_2 = \omega_{eg}$

Assume *v* small, Taylor expand about δ=0

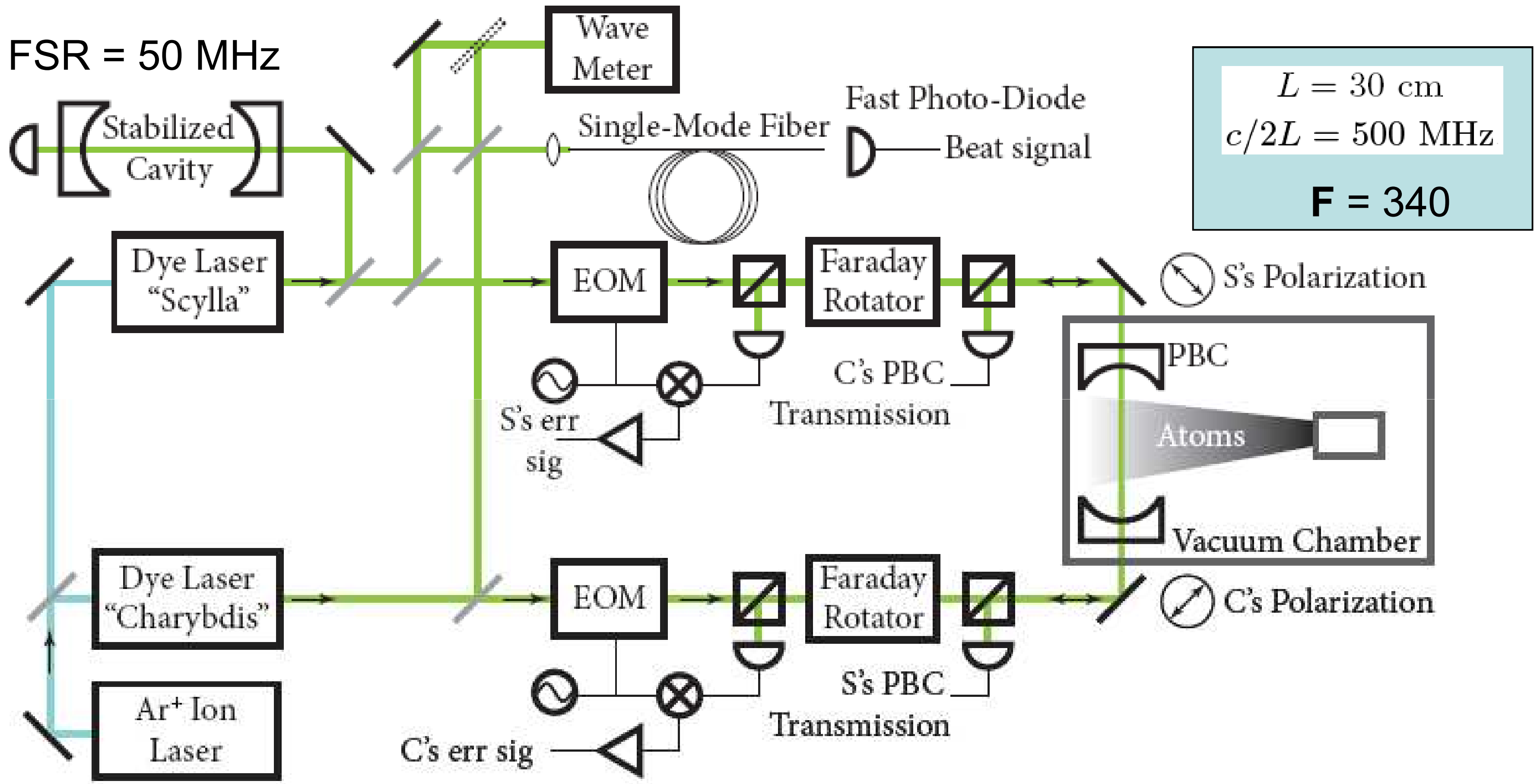
$$W_{-}(\delta) = \frac{2\,\mathcal{D}_{en}^2 \mathcal{D}_{ng}^2\, \bar{I}_1 \bar{I}_2}{\Gamma \hbar^4 \Delta^2 \epsilon_0^2\, c^2} \left(1 - \frac{\delta^2}{\Delta^2}\right)^{-2}$$

$$W_{+}(\delta) = \frac{\delta^2}{\Delta^2} W_{-}(\delta)\,.$$

$$\mathcal{S}_{\rm cal} = \mathcal{S}(\delta_{\rm cal}) = \gamma W_{-}(0)\, \frac{\delta_{\rm cal}^2}{\Delta^2} + \mathcal{O}\left(\frac{\delta_{\rm cal}^4}{\Delta^4}\right)$$

$$\mathcal{S}_{\rm lim} = \mathcal{S}(0) = \gamma \nu\, W_{-}(0)$$

$$\nu = \frac{\mathcal{S}_{\rm lim}}{\mathcal{S}_{\rm cal}}\, \frac{\delta_{\rm cal}^2}{\Delta^2}.$$



FSR = 50 MHz
Stabilized Cavity
Wave Meter
Single-Mode Fiber
Fast Photo-Diode
Beat signal
$L = 30$ cm
$c/2L = 500$ MHz
F = 340
Dye Laser "Scylla"
EOM
Faraday Rotator
S's Polarization
PBC
Atoms
Vacuum Chamber
S's err sig
C's PBC Transmission
Dye Laser "Charybdis"
EOM
Faraday Rotator
C's Polarization
Ar+ Ion Laser
C's err sig
S's PBC Transmission

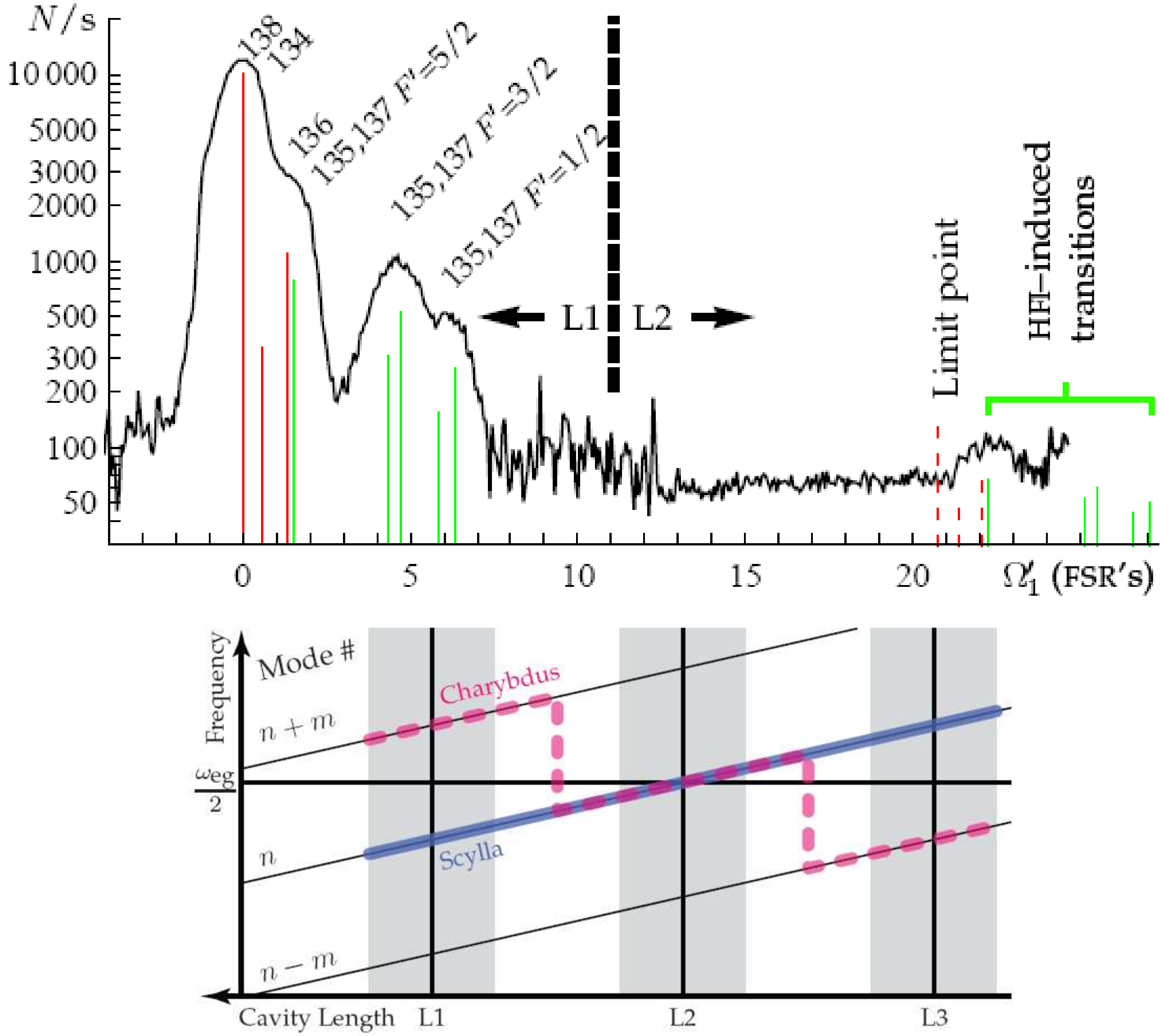
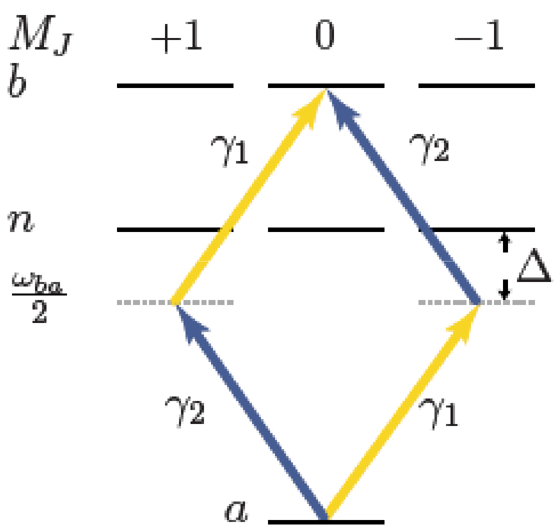
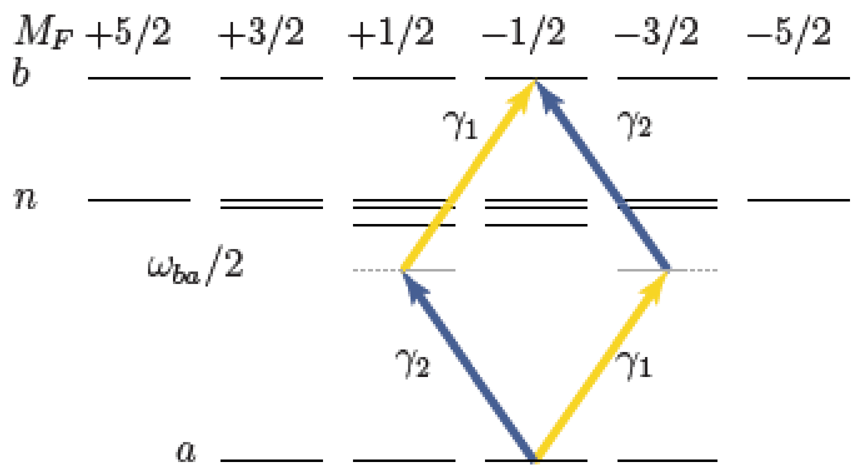


FIG. 5. (color online). Laser tuning path during run. The lasers are tuned in concert with the PBC, either separated by m=4 longitudinal cavity modes, or in the same mode.

HFI-induced transitions





$$\mathcal{S}(\delta) = \gamma \{W_{+}(\delta) + \nu W_{-}(\delta)\}$$

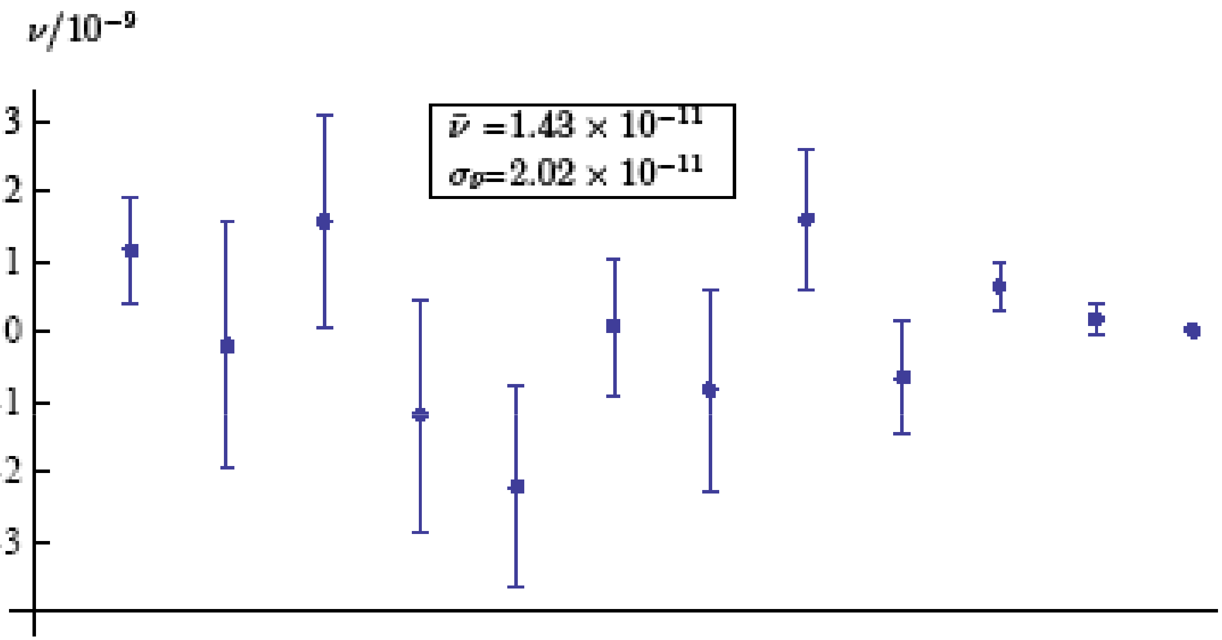


FIG. 7. (color online). ν from twelve runs. The error bars decrease over the lifetime of the experiment as improvements in excitation and detection efficiency were achieved.

Systematic errors

- False positives
  - Ba-137 (11%) and Ba-135 (6.6%), I≠0
    - Hyperfine splitting breaks symmetry between paths leading to imperfect destructive interference. $\approx 10^{-9}$
  - Zeeman splitting due to b/g magnetic fields $\approx 10^{-11}$ @ 10 G
  - Non-zero spectral width of lasers (3 MHz) $\approx 10^{-12}$
  - Line broadening due to transverse atomic motion (13 MHz) $\approx 10^{-15}$
  - Light shifts $\approx 10^{-12}$
  - E1M2, E2M1 transitions $\approx 10^{-19}$

Conclusion

- Photons: still bosons*.

  * to 1 part in 10^{11}

(I think…)