A Spectroscopic Test of the Bose-Einstein Statistics of Photons

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The principle of the experiment

According to the Landau-Yang theorem, there are some things bosonic photons simply won’t do.

Initial

\[ \vec{\epsilon}_1, \vec{k}_1 \]

Final

\[ \vec{\epsilon}_2, \vec{k}_2 \]

Decay of vector particle V to two photons, in the rest frame of V, \( k_1 = -k_2 \).

C. N. Yang, Phys. Rev. 77, 242 (1950)
The principle of the experiment

There are some things bosonic photons simply won’t do.

Decay of vector particle $V$ to two photons, in the rest frame of $V$, $k_1 = -k_2$.

Final state 2-$\gamma$ WF must be proportional to...

\[
\vec{\epsilon}_1 \times \vec{\epsilon}_2
\]

or...

\[
(\vec{\epsilon}_1 \cdot \vec{\epsilon}_2) \vec{k}
\]

or...

\[
\vec{k} \times (\vec{\epsilon}_1 \times \vec{\epsilon}_2) = \vec{\epsilon}_1 \left( \vec{k} \cdot \vec{\epsilon}_2 \right) - \vec{\epsilon}_2 \left( \vec{k} \cdot \vec{\epsilon}_1 \right)
\]
T-reversed LY violation in atoms.

Barium

<table>
<thead>
<tr>
<th>Isotope</th>
<th>NA (%)</th>
<th>I</th>
</tr>
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<tbody>
<tr>
<td>$^{138}\text{Ba}$</td>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>$^{137}\text{Ba}$</td>
<td>11</td>
<td>3/2</td>
</tr>
<tr>
<td>$^{136}\text{Ba}$</td>
<td>7.8</td>
<td>0</td>
</tr>
<tr>
<td>$^{135}\text{Ba}$</td>
<td>6.6</td>
<td>3/2</td>
</tr>
<tr>
<td>$^{134}\text{Ba}$</td>
<td>2.4</td>
<td>0</td>
</tr>
</tbody>
</table>

$\Delta = 93 \text{ cm}^{-1}$

$40000 \text{ (cm}^{-1})$

$36447 \ 5d6d \ ^3S_1$

$35934 \ 5d6d \ ^3D_1$

$11395 \ 6s5d \ ^1D_2$

$9597 \ 6s5d \ ^3D_3$

$9216 \ 6s5d \ ^3D_2$

$9034 \ 6s5d \ ^3D_1$

$18060 \ 6s6p \ ^1P_1$

$13514 \ 6s6p \ ^3P_2$

$12636 \ 6s6p \ ^3P_1$

$12266 \ 6s6p \ ^3P_0$

$6s^2 \ ^1S_0$
Atomic two-$\gamma$ transition

$$W = \frac{2\pi}{\hbar^4} \times \left| \sum_n \left( \frac{\mathcal{A}^{(n)}_{12}}{\omega_{ng} - \Omega_2 + i\Gamma_n/2} \right) \right|^2 + \left( \frac{\mathcal{A}^{(n)}_{21}}{\omega_{ng} - \Omega_1 + i\Gamma_n/2} \right)$$

$$\times \frac{1}{\pi} \frac{\frac{\Gamma}{2}}{\left( \Omega_1 + \Omega_2 - \omega_{eg} \right)^2 + \left( \Gamma/2 \right)^2} \frac{\bar{I}_1 \bar{I}_2}{4\epsilon_0^2 c^2},$$

$|g\rangle, |n\rangle, |e\rangle$: ground-, intermediate-, excited-state

$\Gamma_n, \Gamma$: intermediate-, excited-state natural widths

$\hat{e}_{1,2}, \Omega_{1,2}$: polarization & energy of photon 1,2

$\omega_{kl} \equiv \omega_k - \omega_l$: energy difference between states $k$ & $l$

$\mathcal{D}$: Dipole moment operator
Atomic two-γ transition

\[ W_{\pm} = \frac{2\pi}{\hbar^4} \times \left| \sum_n \frac{\langle e | \hat{\epsilon}_1 \cdot \mathcal{D} | n \rangle \langle n | \hat{\epsilon}_2 \cdot \mathcal{D} | g \rangle}{\omega_{ng} - \Omega_2 + i\Gamma_n/2} \pm \frac{\langle e | \hat{\epsilon}_2 \cdot \mathcal{D} | n \rangle \langle n | \hat{\epsilon}_1 \cdot \mathcal{D} | g \rangle}{\omega_{ng} - \Omega_1 + i\Gamma_n/2} \right|^2 \]

\[ \times \frac{1}{\pi} \frac{\Gamma/2}{\left(\Omega_1 + \Omega_2 - \omega_{eg}\right)^2 + (\Gamma/2)^2} \frac{I_1 I_2}{4\epsilon_0^2 c^2} \]

\[ |g\rangle, |n\rangle, |e\rangle : \text{ground-, intermediate-, excited-state} \]

\[ \Gamma_n, \Gamma : \text{intermediate-, excited-state natural widths} \]

\[ \hat{\epsilon}_{1,2}, \Omega_{1,2} : \text{polarization & energy of photon 1,2} \]

\[ \omega_{kl} \equiv \omega_k - \omega_l : \text{energy difference between states } k \text{ & } l \]

\[ \mathcal{D} : \text{Dipole moment operator} \]
Atomic two-$\gamma$ transition \( J = 0 \rightarrow J' = 1 \)

\[
W_{\pm} = \frac{2\pi}{\hbar^4} \times \frac{\mathcal{D}_1^2 \mathcal{D}_2^2}{2} \left| f_{\pm} \right|^2 \\
\times \frac{1}{\pi} \frac{\Gamma/2}{(\Omega_1 + \Omega_2 - \omega_{eg})^2 + (\Gamma/2)^2} \frac{\vec{I}_1 \cdot \vec{I}_2}{4\epsilon_0^2 c^2}
\]

\(|g\rangle, |n\rangle, |e\rangle\) : ground-, intermediate-, excited-state

\(\Gamma_n, \Gamma\) : intermediate-, excited-state natural widths

\(\hat{e}_{1,2}, \Omega_{1,2}\) : polarization & energy of photon 1,2

\(\omega_{kl} \equiv \omega_k - \omega_l\) : energy difference between states \(k\) & \(l\)

\(\mathcal{D}\) : Dipole moment operator
Atomic two-γ transition \[ J = 0 \rightarrow J' = 1 \]

\[ W_\pm = \frac{2\pi}{\hbar^4} \times \frac{D_1^2 D_2^2}{2} \left| f_\pm \right|^2 \times \frac{1}{\pi} \frac{\Gamma/2}{(\Omega_1 + \Omega_2 - \omega_{eg})^2 + (\Gamma/2)^2} \frac{\bar{I}_1 \bar{I}_2}{4 \xi_0^2 c^2} \]

\[ \left| f_\pm \right|^2 \]

\[ \frac{1}{\Delta^2} \]
Atomic two-$\gamma$ absorption

\[ W_- = \frac{2D_1^2D_2^2\bar{I}_1\bar{I}_2}{\Gamma \hbar^4 \Delta^2 \epsilon_0^2 c^2} \left( 1 + \frac{\delta^2}{\Delta^2} \right)^{-2} \]

\[ W_+ = W_- \frac{\delta^2}{\Delta^2} \]

\[ W_{\text{measured}} = W_+ + \nu W_- + W_{\text{backgrounds}} \]

\[ \implies \nu \leq \nu_{\text{limit}} = \frac{W_{\text{backgrounds}}}{W_-} \]

\[ \implies \nu_{\text{limit}} \propto W_{\text{backgrounds}} \times \frac{\Gamma \Delta^2}{D_1^2D_2^2\bar{I}^2} \]

\[ \nu = \frac{S(\omega_H)}{S(\omega_H + \delta)} \frac{\delta^2}{\Delta^2} \]
Summary of Previous Experiment

Search for Exchange-Antisymmetric Two-Photon States

D. DeMille,1 D. Budker,2 N. Derr,3,* and E. Deveney3,†

[Diagram showing energy levels and transitions]
Summary of Previous Experiment

- $\nu = 1.2 \times 10^{-7}$
- Ba vapor cell
- Pulsed lasers
- Limited by laser linewidth

FIG. 3. Typical scan through the nondegenerate calibration transition (points) and fit to determine peak height and linewidth (solid line). Taken with 230 $\mu$L/pulse at 566 nm and 0.4 $\mu$L/pulse at 532 nm.

FIG. 4. Scans through the degenerate transition and best fits to peak plus background.
The New Apparatus
New Apparatus: Optical Schematic
New Apparatus: Laser linewidth

FFT of Two-Laser Beat Signal

δf ~ 1MHz
One scan.
$\nu (10^{-9})$

$\nu_{\text{limit}} = \bar{\nu} + 1.28 \sigma = 7.4 \times 10^{-10}$.

$\bar{\nu} = 0.414 \times 10^{-9}$

$\sigma_{\bar{\nu}} = 0.255 \times 10^{-9}$

http://leo.berkeley.edu/dethesis.pdf
Since 2007…

- Better light-collection
- Tighter focused laser beams
- New Dye pump
- … + many more small improvements
Raw data from one day’s run, $\nu=1\times10^{-10}$
Conclusions

• 3 OOM improvement over DeMille et al. (1999)

• 1 to 2 more OOM to come in relatively short time.

Greetings from the Budker group!