Autler-Townes Splitting as a Quantum Memory Scheme

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2018/8/17
Outline

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Introduction to Autler-Townes splitting (ATS)
Autler-Townes Splitting

\[
\Omega_c = 0 \\
\delta \approx \Omega_c
\]
Autler-Townes Splitting

- A $\Lambda$-type three level system
- The Hamiltonian of the atom interacting with both probe and coupling laser is

\[
H_{\text{int}} = \hbar (\Delta_1 - \Delta_2) |2\rangle\langle 2| + \hbar \Delta_1 |3\rangle\langle 3| - \frac{\hbar \Omega_p}{2} (|1\rangle\langle 3| + |3\rangle\langle 1|) - \frac{\hbar \Omega_c}{2} (|2\rangle\langle 3| + |3\rangle\langle 2|)
\]
Autler-Townes Splitting

• For $\Delta_1 = \Delta_2 = \Delta$, the eigenstates are
  
  $|a^0\rangle = \cos \theta |1\rangle - \sin \theta |2\rangle$
  
  $|a^+\rangle = \sin \theta \sin \phi |1\rangle + \cos \phi |3\rangle + \cos \theta \sin \phi |2\rangle$
  
  $|a^-\rangle = \sin \theta \cos \phi |1\rangle - \sin \phi |3\rangle + \cos \theta \cos \phi |2\rangle$

• Where

  $\tan \theta = \frac{\Omega_p}{\Omega_c}, \tan 2\phi = \frac{\sqrt{\Omega_p^2 + \Omega_c^2}}{\Delta}$
Autler-Townes Splitting

• Given a weak probe field ($\Omega_p \ll \Omega_c$):

$$|a^0\rangle = |1\rangle$$
$$|a^+\rangle = \cos \phi |3\rangle + \sin \phi |2\rangle$$
$$|a^-\rangle = -\sin \phi |3\rangle + \cos \phi |2\rangle$$

with eigenvalues $E^0 = 0$, $E^{\pm} = \frac{\hbar}{2}(\Delta \pm \sqrt{\Delta^2 + \Omega_c^2})$

• And if $\Delta = 0$:

$$|a^{\pm}\rangle = \frac{1}{\sqrt{2}}(|2\rangle \pm |3\rangle), \quad E^{\pm} = \pm \frac{\hbar \Omega_c}{2}$$
ATS as a quantum memory scheme
OBE of the Atom-Light System for N Atoms

• \((\partial_t + c\partial_z)E(z, t) = ig\sqrt{N}P(z, t)\)

• \(\partial_t P(z, t) = -\gamma_e P(z, t) + ig\sqrt{N}E(z, t) + \frac{i}{2}\Omega_c S(z, t)\)

• \(\partial_t S(z, t) = -\gamma_e S(z, t) + \frac{i}{2}\Omega^*P(z, t)\)

• \(|S(z, t)|^2 \propto \cos^2 \frac{A_c(t)}{2}\) ← Oscillation with a period of \(A_c(t) = 2\pi\)

• \(|E(z, t)|^2 \propto \sin^2 \frac{A_c(t)}{2}\)

(where \(A_c(t) = \int_0^t \Omega_c(t')dt'\))
The ATS Quantum Memory Protocol

$$\delta_A \approx 2\pi B_{\text{FWHM}}$$
Experimental Demonstration of ATS Memory

\[ \Omega_c(t) \approx \delta_A(t) \propto \sqrt{P(t)} \]
The ATS memory efficiency
The ATS Memory Efficiency

\[ \eta = \frac{\int_T^\infty |E(L,t)|^2 \, dt}{\int_{0}^T |E(0,t)|^2 \, dt} = \eta_s \eta_r \eta_d \]

- s: storage, r: retrieval, d: spin-wave decoherence.

- \( \eta_s = \mu_w(A_c^{\text{write}})\mu_{\text{abs}}(d, \Gamma, \Omega_c^{\text{write}}) \)

- \( \eta_r = \mu_r(A_c^{\text{read}})\mu_{\text{re}}(d, \Gamma, \Omega_c^{\text{read}}) \)

- \( \mu_w, \mu_r \): polarization-mediated reversible transfer between spin-wave and photonic modes in writing/reading

- \( \mu_{\text{abs}} \): absorption probability, \( \mu_{\text{re}} \): re-emission probability
Memory Efficiency with Different Pulse Areas
The ATS Memory Efficiency

• Assuming $\eta_d \approx 1$, $A_c^{\text{write}} = A_c^{\text{read}} = 2\pi$:
  \[
  \eta = \mu_{\text{abs}} \mu_{\text{re}}
  \]

• The light can be retrieved in different directions:
  • Forward propagating: $\eta_f = \tilde{d}^2 e^{-\tilde{d}} \mu_d \approx \left(\frac{d}{2F}\right)^2 e^{-d/2F} e^{-1/F}$
  • Backward propagating: $\eta_b = (1 - e^{-\tilde{d}})^2 \mu_d \approx (1 - e^{-d/2F})^2 e^{-1/F}$

• $\tilde{d} = d/2F$: effective optical depth
• $F = \Omega_c/\Gamma$: ATS factor
• $\mu_d = e^{-1/F}$: coherence survival probability for polarization

Large optical depth increases collective absorption and re-emission probability

But also increases the re-absorption probability of the emitted photons

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• $\tilde{d} = d/2F$: effective optical depth
• $F = \Omega_c/\Gamma$: ATS factor
• $\mu_d = e^{-1/F}$: coherence survival probability for polarization
Re-absorption of the Retrieved Light

c. $d = 40, \ F = 12$

d. $d = 85, \ F = 12$
Specialties of ATS memory
Dynamically Controllable Storage Bandwidth

• Optimal writing requires $A_c^{\text{write}}(\tau) = 2\pi$, where $\tau \propto 1/B_{\text{FWHM}}$

• Increasing the bandwidth requires increasing $\Omega_c(t) \propto \sqrt{P(t)}$
Temporal Compression and Stretching

• Provided that $\Omega_c(t)$ is set to give $A_c^{\text{read}}(\tau) = 2\pi$, the read-out can be longer or shorter than the input.
Temporal Beam Splitting
Discerning ATS from EIT
Discerning ATS from EIT

Objectively Discerning Autler-Townes Splitting from Electromagnetically Induced Transparency

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Received 2 February 2011; published 12 October 2011

Autler-Townes splitting (ATS) and electromagnetically induced transparency (EIT) both yield transparency in an absorption profile, but only EIT yields high transparency for a weak pump field due to Fano interference. Empirically discriminating EIT from ATS is important but so far has been subjective. We introduce an objective method, based on Akaike’s information criterion, to test ATS vs EIT from experimental data for three-level atomic systems and determine which principles apply. We method to a recently reported induced-transparency experiment in superconducting-circuit quantum electrodynamics.

DOI: 10.1103/PhysRevLett.107.163604
PACS numbers: 42.50.Gy, 42.50.Ct

Experimental investigation of the transition between Autler-Townes splitting and electromagnetically-induced-transparency models


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(Received 25 June 2012; published 22 January 2013)

Two phenomena can affect the transmission of a probe field through an absorbing medium in the presence of an additional field: electromagnetically induced transparency (EIT) and Autler-Townes splitting (ATS). Being able to discriminate between the two is important for various practical applications. Here we present an experimental investigation into a method that allows for such a disambiguation as proposed by Anisimov, Dowling, and Sanders in Phys. Rev. Lett. 107, 163604 (2011). We apply the proposed test based on Akaike’s information criterion to a coherently driven ensemble of cold cesium atoms and find a good agreement with theoretical predictions, therefore demonstrating the suitability of the method. Beyond the applicability of the test, our results demonstrate that the transition features are highly sensitive to the properties of the medium under study, potentially providing a characteristicizing tool for complex systems.

DOI: 10.1103/PhysRevA.87.013823
PACS number(s): 42.50.Gy, 03.67.–a, 42.50.Ct
Discerning ATS from EIT: Theoretical Foundation

• The EM response to the probe is proportional to the density matrix element $\sigma_{ab}$.

• For $\Delta = 0$ (resonant coupling field), the steady state solution to first order of $\alpha$ is:

$$\sigma_{ab} = \frac{\alpha(\delta - i\Gamma_{bc})}{-\Omega^2 + (\delta - i\Gamma_{ab})(\delta - i\Gamma_{bc})}$$
Discerning ATS from EIT: Theoretical Foundation

- The linear absorption $A \propto \text{Im}(\sigma_{ab})$ is composed of two parts:

$$A_{\pm} = \frac{S_{\pm}}{\delta - \delta_{\pm}}$$

- whose centers and strengths are

$$\delta_{\pm} = \frac{i(\Gamma_{ab} + \Gamma_{bc})}{2} \pm \sqrt{\Omega^2 - (\Gamma_{ab} - \Gamma_{bc})^2/4}$$

- and

$$S_{\pm} = \pm \frac{\delta_{\pm} - i\Gamma_{bc}}{\delta_{+} - \delta_{-}}$$

- respectively.
Discerning ATS from EIT: Theoretical Foundation

• These two resonance contributions $A_{\pm}$ can be attributed to two “decaying-dressed states” with frequencies $\text{Re}(\delta_{\pm})$ and dephasing rates $\text{Im}(\delta_{\pm})$ respectively.
Discerning ATS from EIT: Theoretical Foundation

• Depending on the value of $\Omega$, the absorption can be divided into three categories:
  
  • (i) $\Omega < \Omega_{EIT} = (\Gamma_{ab} - \Gamma_{bc})/2$, so that $\text{Re}(\delta_{\pm}) = 0 = \text{Im}(S_{\pm})$.
  
  • (ii) $\Omega \gg \Gamma_{ab}$, so that $\delta_{\pm} \approx \pm\Omega + \frac{i(\Gamma_{ab} + \Gamma_{bc})}{2}$ and $S_{\pm} \approx 1/2$.
  
  • (iii) intermediate regime between (i) and (ii).
Discerning ATS from EIT: Theoretical Foundation

• In $\Omega$-region (i): $\text{Re}(\delta_\pm) = 0 = \text{Im}(S_\pm)$

• The absorption profile consists two Lorentzian curve centered at the origin, with different widths and strengths.

\[
A_{EIT} = \frac{C_+^2}{\gamma_+^2 + \delta^2} - \frac{C_-^2}{\gamma_-^2 + \delta^2}
\]

• In $\Omega$-region (ii): $\delta_\pm \approx \pm \Omega + \frac{i(\Gamma_{ab} + \Gamma_{bc})}{2}$ and $S_\pm \approx 1/2$

• The absorption profile is the sum of two equal-width Lorentzian curves shifted from the origin by $\pm \Omega$.

\[
A_{ATS} = C^2 \left[ \frac{1}{\gamma^2 + (\delta - \delta_0)^2} + \frac{1}{\gamma^2 + (\delta + \delta_0)^2} \right]
\]
Discerning ATS from EIT: Theoretical Foundation

\[ \Omega \gg \Gamma_{ab} : \text{ATS regime} \]

\[ \Omega < \Omega_{EIT} : \text{EIT regime} \]
Discerning ATS from EIT Empirically

• Two models $A_{EIT}, A_{ATS}$ and one set of data $D = \{A(\delta_j)\}$.

• Fit both models to the set of data.

• Use Akaike’s Information Criterion (AIC) to identify the most informative model.
Discerning ATS from EIT Empirically

• The AIC of model $A_i$ is given by

$$I_i = -2\log\mathcal{L}_i + 2K_i$$

which measures the relative information lost when a model is considered as the process that generates the data.

• And the Akaike weight is given by

$$w_i = e^{-\frac{I_i}{2}}$$

$$\frac{w_i}{\sum_k e^{-\frac{I_k}{2}}}$$

which represents the relative likelihood that model $A_i$ is the best model out of all the candidates.
Discerning ATS from EIT Empirically

*Fitting both models (ATS: green dashed, EIT: blue solid) to theoretically calculated absorption profile (red dots)
Discerning ATS from EIT Empirically

• Theoretically, the Akaike weight $w_i$ should be averaged on a per-run basis.

• Another criterion is proposed: per-point weight $\bar{w}_i$

$$\bar{w}_i = \frac{e^{-\frac{I_i}{2N}}}{\sum_k e^{-\frac{I_k}{2N}}}$$
Discerning ATS from EIT Empirically

No noise

Gaussian noise ($\sigma=0.01$)

Gaussian noise ($\sigma=0.1$)
Discerning ATS from EIT: Experimental Investigation

(a) Laser diode

(b) Absorption A vs. \( \delta \) (MHz)

(c) Spliting (MHz) vs. \( nP \) (nW)

\[ \alpha = 1670 \pm 100 \text{ MHz/nW} \]
Discerning ATS from EIT: Experimental Investigation

• Two models:

\[ A_{EIT} = \frac{C_+^2}{\gamma_+^2 + (\delta - \epsilon)^2} - \frac{C_-^2}{\gamma_-^2 + \delta^2} \]

\[ A_{ATS} = \frac{C_1^2}{\gamma_1^2 + (\delta + \delta_1)^2} + \frac{C_2^2}{\gamma_2^2 + (\delta - \delta_2)^2} \]
Discerning ATS from EIT: Experimental Investigation

Theoretical per-point weights for a pure three-level system
Discerning ATS from EIT: Experimental Investigation

• The deviation results from several features of the system that cannot be described by a simple three-level model:

• (i) The other hyperfine sublevels of the $6P_{3/2}$ manifold (still only two ground states)
• (ii) The other Zeeman sublevels (multiple three-level systems)
• (iii) Doppler broadening $\Gamma_D$
Discerning ATS from EIT: Experimental Investigation

Theoretical calculation taking into account:
- Gray solid: (i)
- Dotted: (i)+(ii)
- Dashed: (i)+(ii)+(iii) with $\Gamma_D/2\pi = 0.6$ MHz
- Dash-dotted: (i)+(ii)+(iii) with $\Gamma_D/2\pi = 1.3$ MHz
References

Q&A