Atom-Photon Entanglement and Magnetometry in Yb

E.A. Alden, S.M. Degenkolb, K.R. Moore, T.E. Chupp, and A.E. Leanhardt

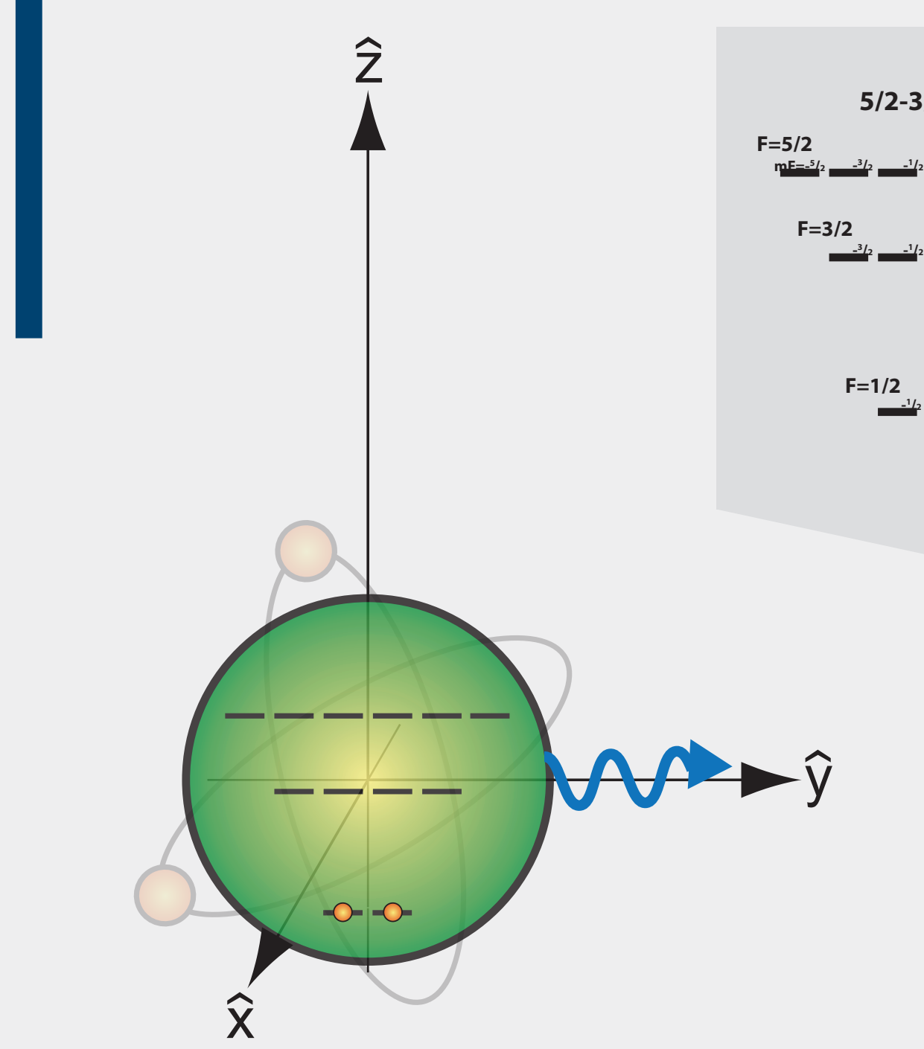
Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA

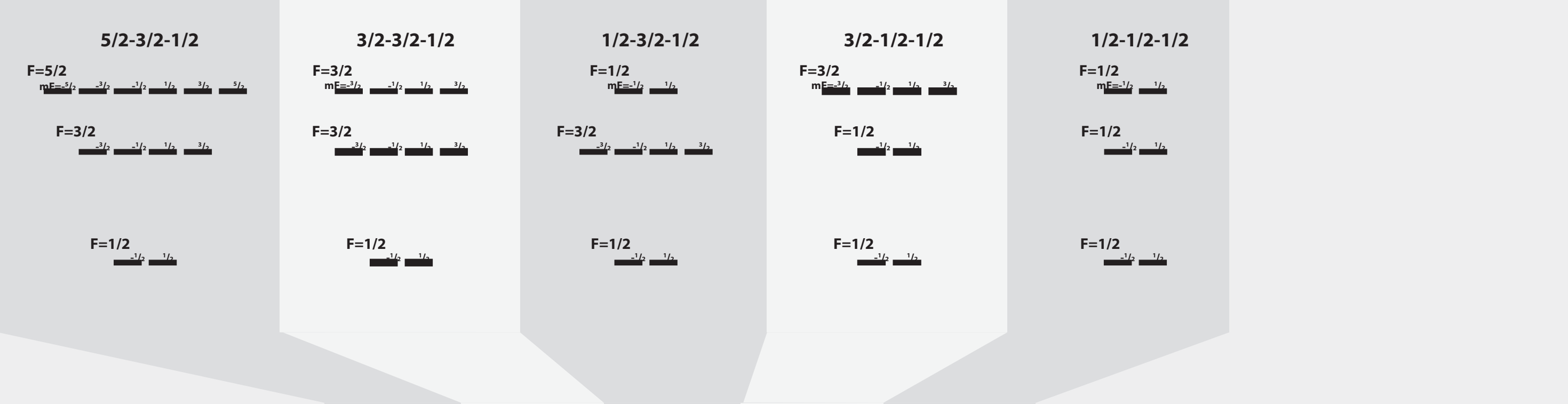
70 $^1S_0$
Yb
Ytterbium
173.04
[Xe]4f^{14}6s^2
6.2542

Tripartite Entangled States in Two-Photon Cascades

There are two classes of entangled tripartite states, W and GHZ type. Both of these classes can be immediately generated from two-photon cascades in atomic systems.

Dipole selection rules only allow ΔF=±1,0. Levels must connect to mF=1/2 ground state.





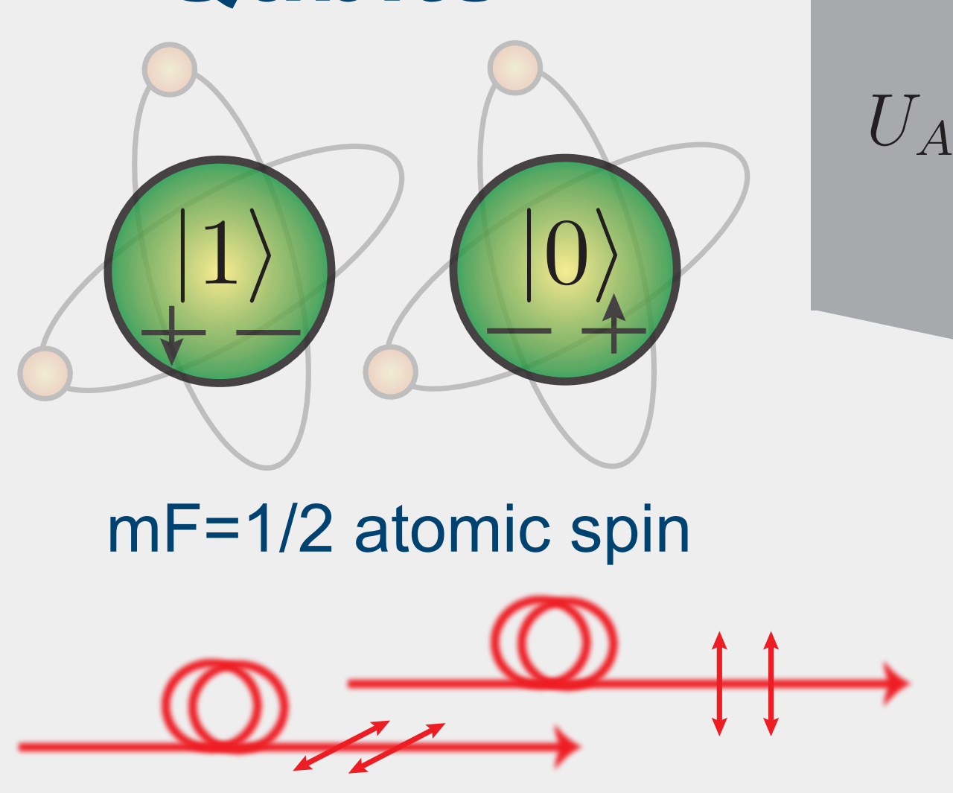
$\hat{k}p,\hat{k}1,\hat{k}2$	$\frac{5}{2}-\frac{3}{2}-\frac{1}{2}$	$\frac{3}{2}-\frac{3}{2}-\frac{1}{2}$	$\frac{1}{2}-\frac{3}{2}-\frac{1}{2}$	$\frac{3}{2}-\frac{1}{2}-\frac{1}{2}$	$\frac{1}{2}-\frac{1}{2}-\frac{1}{2}$
$\hat{x},\hat{x},\hat{x}$	A-BC	A-BC	A-BC	A-B-C	A-B-C
$\hat{x},\hat{x},\hat{y}$	GHZ	GHZ	GHZ	GHZ	GHZ
$\hat{x},\hat{x},\hat{z}$	GHZ	GHZ	GHZ	GHZ	GHZ
$\hat{x},\hat{y},\hat{x}$	GHZ	GHZ	GHZ	C-AB	C-AB
$\hat{x},\hat{y},\hat{y}$	GHZ	GHZ	GHZ	GHZ	GHZ
$\hat{x},\hat{y},\hat{z}$	W	GHZ	GHZ	GHZ	GHZ
$\hat{x},\hat{z},\hat{x}$	GHZ	GHZ	GHZ	C-AB	C-AB
$\hat{x},\hat{z},\hat{y}$	W	GHZ	GHZ	GHZ	GHZ
$\hat{x},\hat{z},\hat{z}$	A-BC	GHZ	GHZ	GHZ	GHZ
$\hat{z},\hat{x},\hat{x}$	GHZ	GHZ	GHZ	GHZ	GHZ
$\hat{z},\hat{x},\hat{y}$	W	GHZ	GHZ	GHZ	GHZ
$\hat{z},\hat{x},\hat{z}$	GHZ	GHZ	GHZ	C-AB	C-AB
$\hat{z},\hat{z},\hat{x}$	GHZ	GHZ	GHZ	GHZ	GHZ
$\hat{z},\hat{z},\hat{z}$	A-BC	A-BC	A-BC	A-B-C	A-B-C

$$|\Psi_{GHZ}\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$$

$$|\Psi_W\rangle = \frac{1}{\sqrt{3}}(|100\rangle + |010\rangle + |001\rangle)$$

A. Ac'in, A. Andrianov, L. Costa, E. Jane, J. I. Latorre, and R. Tarrach, Physical Review Letters 85, 1560 (2000)
W. Dur, G. Vidal, and J. I. Cirac, Physical Review A 62, 062314+ (2000)
V. Coffman, J. Kundu, and W. K. Wootters, Physical Review A 61, 052306+ (2000)

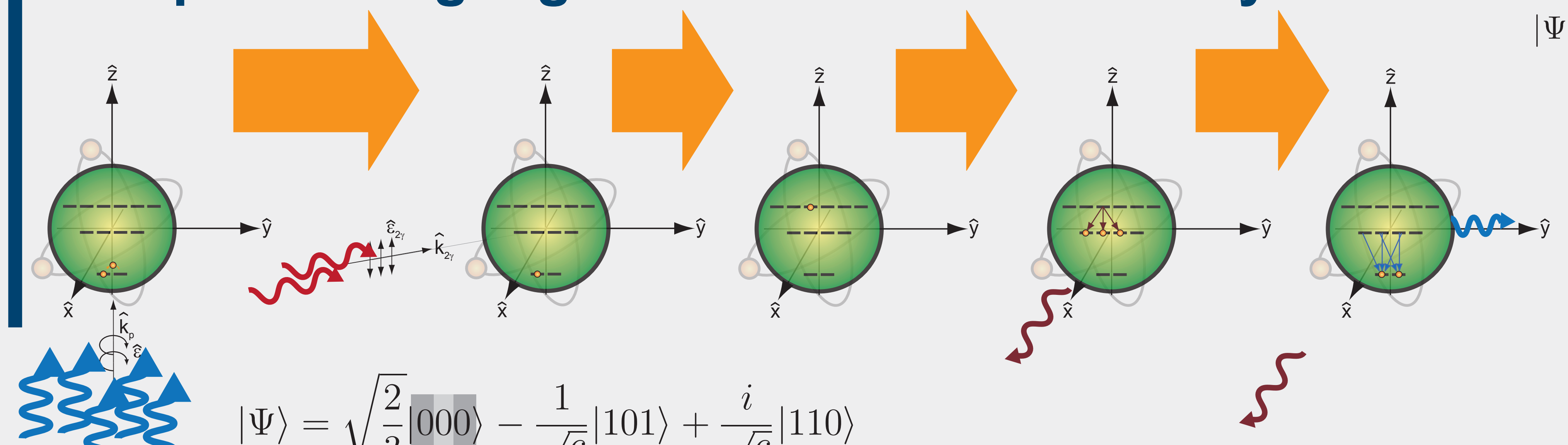
Qubits



mF=1/2 atomic spin

light polarization

Sample Entangling Cascade 5/2-3/2-1/2 z-x-y



$$|\Psi\rangle = \sqrt{\frac{2}{3}}|000\rangle - \frac{1}{\sqrt{6}}|101\rangle + \frac{i}{\sqrt{6}}|110\rangle$$

$$U_A = \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} \quad U_B = \begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix} \quad U_C = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$|\Psi\rangle = \sqrt{\frac{2}{3}}|100\rangle + \frac{1}{\sqrt{6}}|010\rangle + \frac{1}{\sqrt{6}}|001\rangle$$

A two-photon cascade of this type produces a W state. If the states' entanglement is not obvious, it can be rotated with unitary transformation on each qubit into a form that is more transparent.

Atom

$$|\Psi_A\rangle = c_{i\downarrow}|\tfrac{1}{2},-\tfrac{1}{2}\rangle + c_{i\uparrow}|\tfrac{1}{2},\tfrac{1}{2}\rangle$$

$$|0\rangle_A \equiv |\tfrac{1}{2},\tfrac{1}{2}\rangle$$

$$|1\rangle_A \equiv |\tfrac{1}{2},-\tfrac{1}{2}\rangle$$

Photon

$$|\Psi_B\rangle = c_{j\uparrow}|\widehat{\theta_1}\rangle + c_{j\downarrow}|\widehat{\phi_1}\rangle$$

$$|0\rangle_B \equiv |\widehat{\theta_1}\rangle$$

$$|1\rangle_B \equiv |\widehat{\phi_1}\rangle$$

Photon

$$|\Psi_C\rangle = c_{k\uparrow}|\widehat{\theta_2}\rangle + c_{k\downarrow}|\widehat{\phi_2}\rangle$$

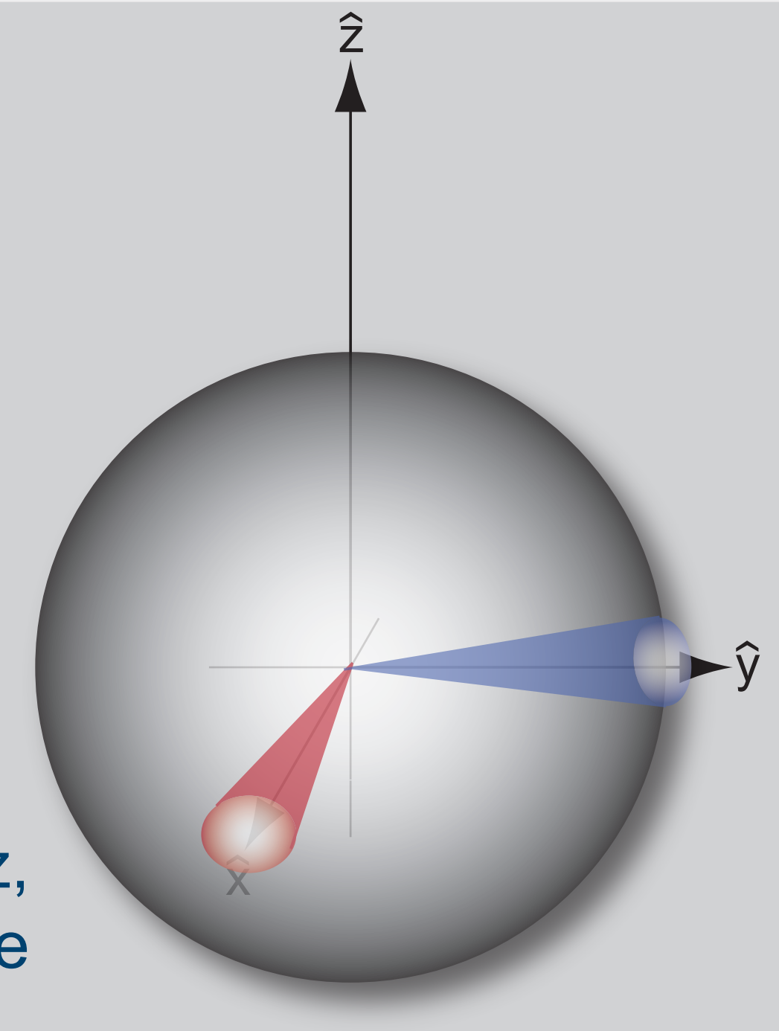
$$|0\rangle_C \equiv |\widehat{\theta_2}\rangle$$

$$|1\rangle_C \equiv |\widehat{\phi_2}\rangle$$

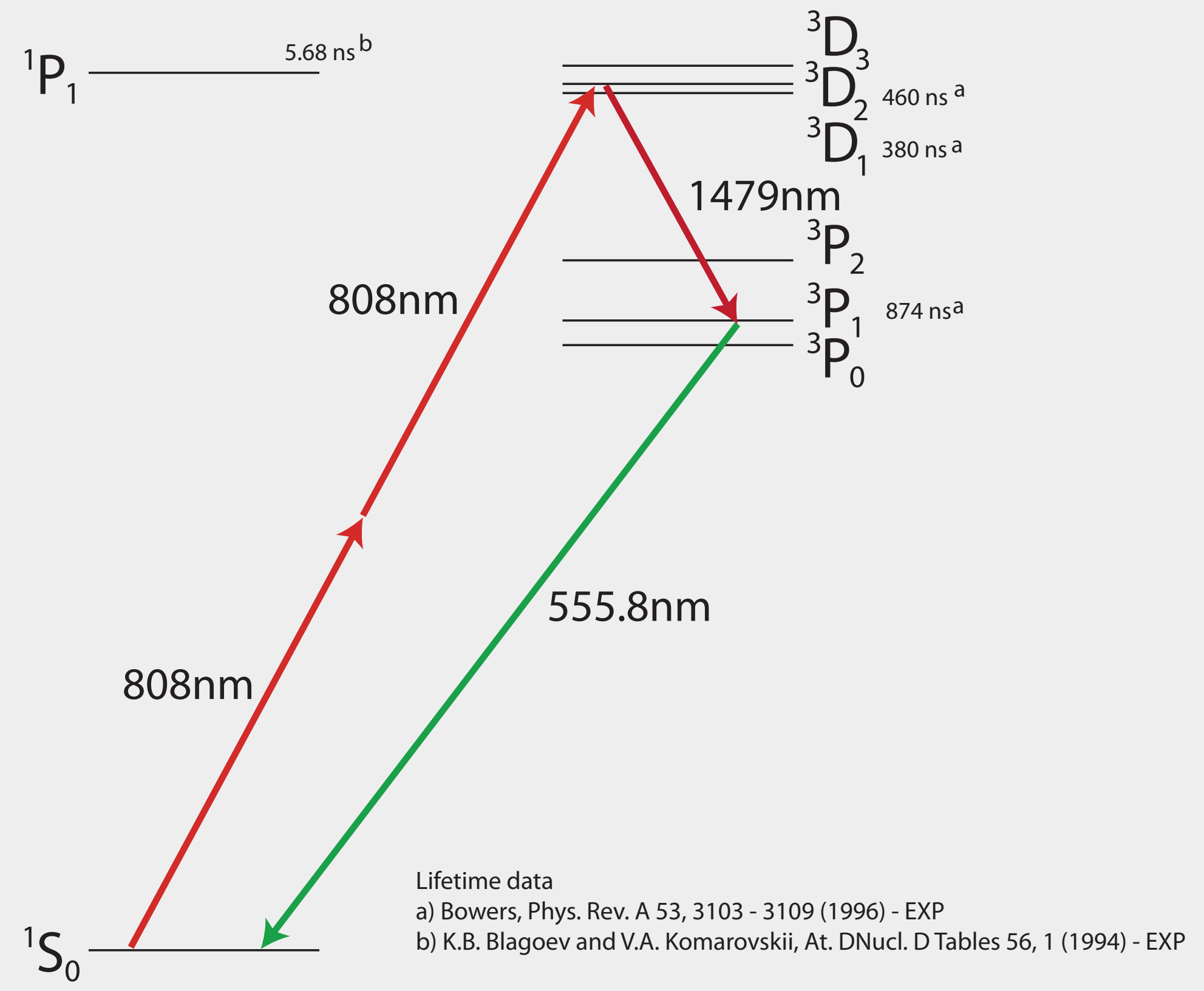
Frequency of Entangling Events
GHZ PD = 1
W PD = 0.675

Quality of Entanglement
W and GHZ type cascades with acceptance angles up to 12°
-maintain 0.9 overlap
-scattering probabilities of 1E-4

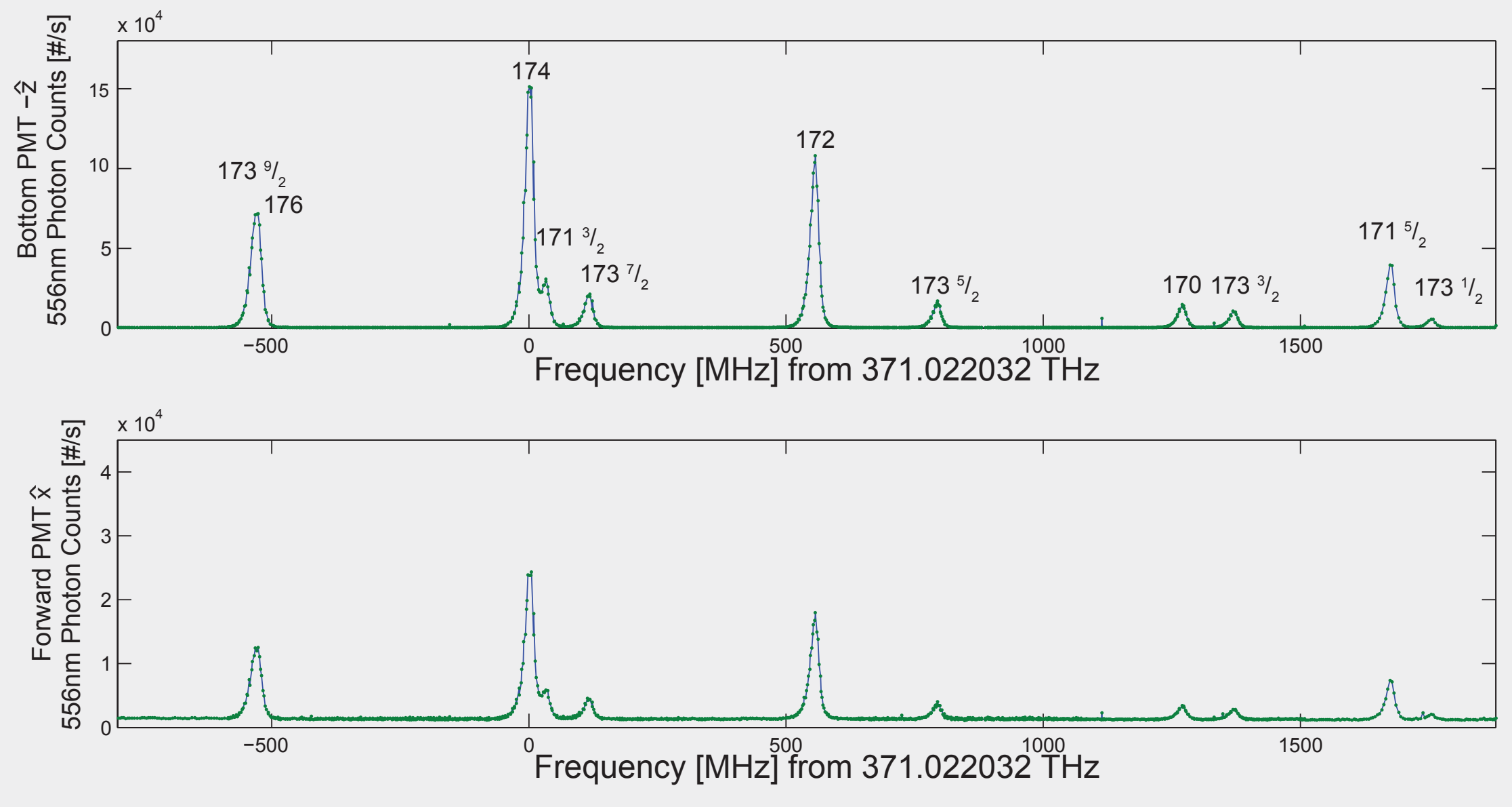
For an atom with decay rate 1E6 Hz, we expect 100Hz entangling cascade rates



Yb Level Structure



Lifetime data
a) Bowers, Phys. Rev. A 53, 3103 - 3109 (1996) - EXP
b) K.B. Blagoev and V.A. Komarovskii, At. DNucl. D Tables 56, 1 (1994) - EXP

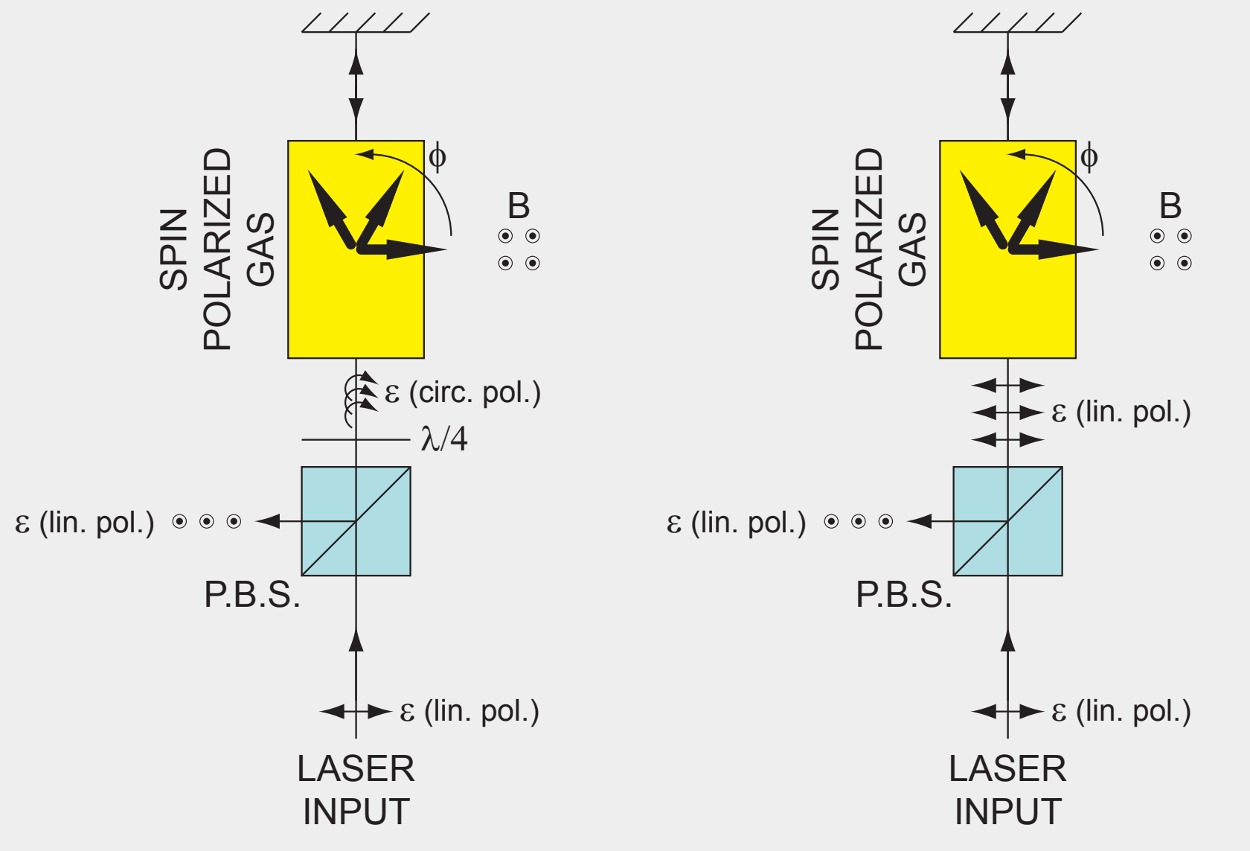


Magnetometry with ^{129}Xe and ^{171}Yb

$$\mathcal{R}(\delta) \approx \rho V \frac{|\mu_{01}|^2|\mu_{12}|^2}{\hbar^4\Delta^2\Gamma}\left(\frac{I}{\epsilon_0 c}\right)^2 \frac{1}{1+\left(\frac{\delta}{\Gamma}\right)^2}$$

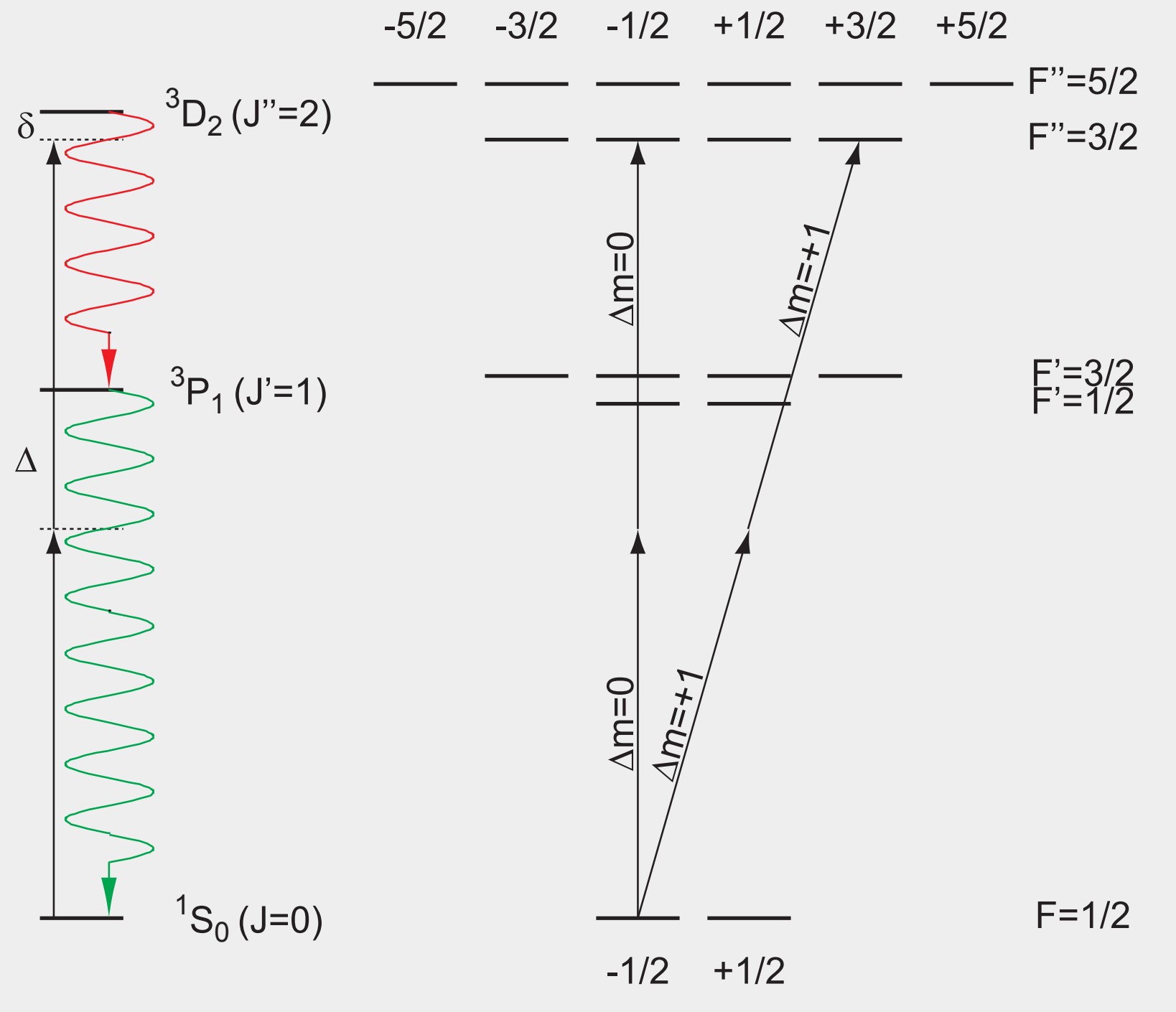
$$n(\delta) \approx 1 + \frac{\rho}{\epsilon_0}\frac{|\mu_{01}|^2|\mu_{12}|^2}{\hbar^3\Delta^2\Gamma}\frac{I}{\epsilon_0 c}\frac{\frac{\delta}{\Gamma}}{1+\left(\frac{\delta}{\Gamma}\right)^2}$$

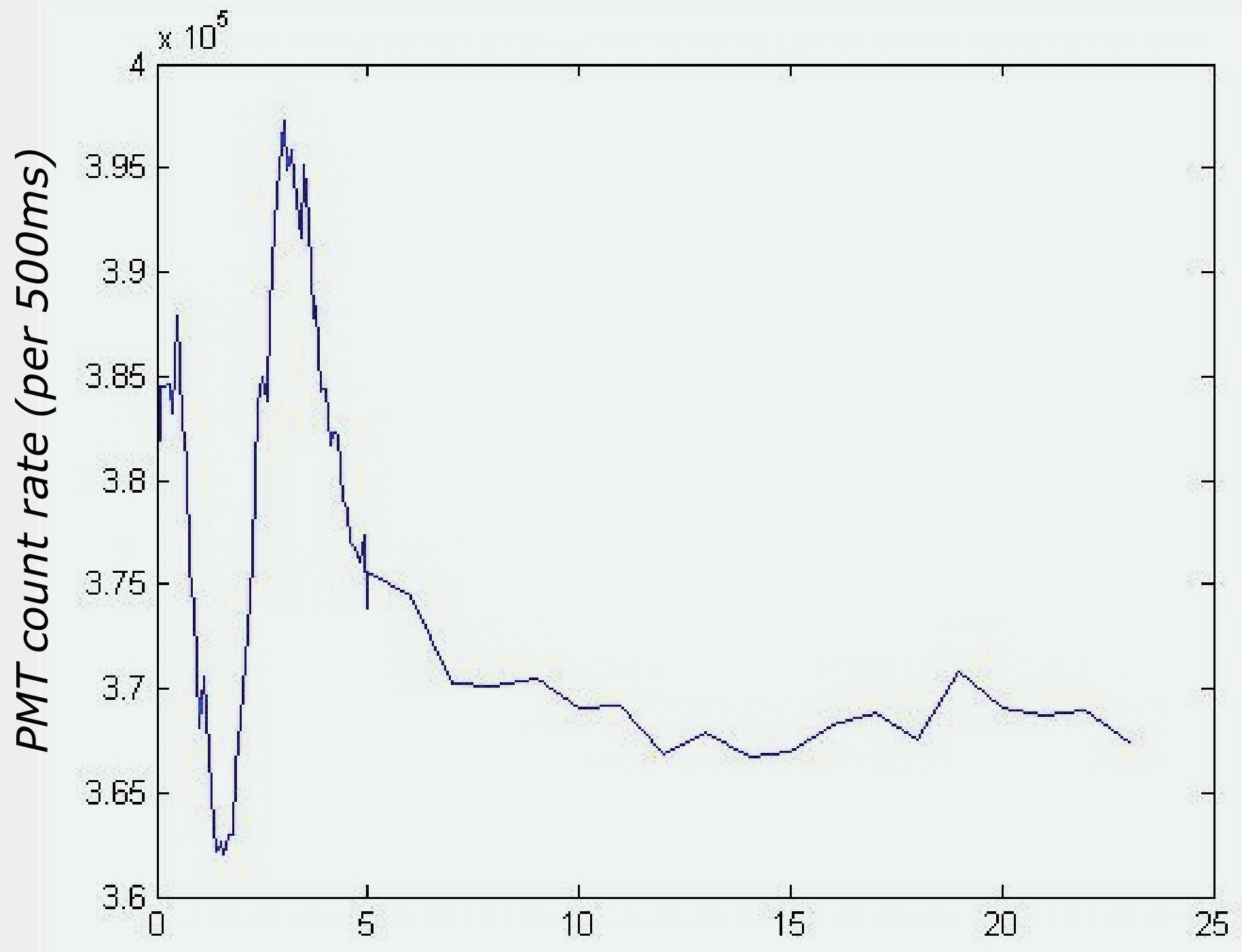
The hyperfine interaction results in two-photon scattering and dispersion which vary with ground-state nuclear spin orientation. Optical probes of these transitions (e.g. absorption, polarization rotation, fluorescence) are sensitive to strength and direction of external magnetic fields. Counting statistics and atomic coherence times limit the precision, and can be exploited to allow real-time measurements with high sensitivity. We present a new technique for precision magnetometry, based on optical monitoring of the $^1S_0 \rightarrow {}^3D_2$ transition in ^{129}Xe.



Probing with circularly polarized light to monitor absorption.

Probing with linear light to monitor polarization rotation.

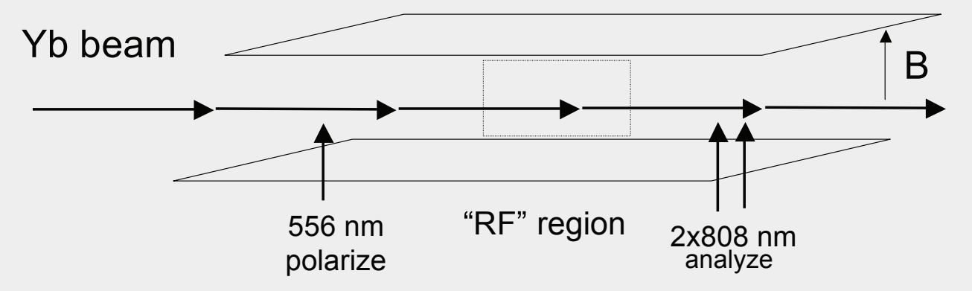




Voltage to liquid crystal waveplate
(retardance is a monotonic function of voltage)

Permanent electric dipole moment (EDM) searches require sensitive, real-time co-magnetometers. For the neutron EDM in particular, ^{129}Xe improves over previous magnetometers with respect to thermal behavior, high-voltage properties, and cross-section for neutron capture.

Polarize ^{171}Yb in a thermal beam by optically pumping the $^1S_0 \rightarrow {}^3P_1$ transition (556 nm). Manipulate with radio frequency fields, probe by driving the $^1S_0 \rightarrow {}^3D_2$ transition and collecting photons from the $^3D_2 \rightarrow {}^3P_1 \rightarrow {}^1S_0$ cascade decay on a photomultiplier. Two-photon absorption rates depend on intensity and polarization of pump light, frequency and magnitude of the quenching field, and probe polarization.

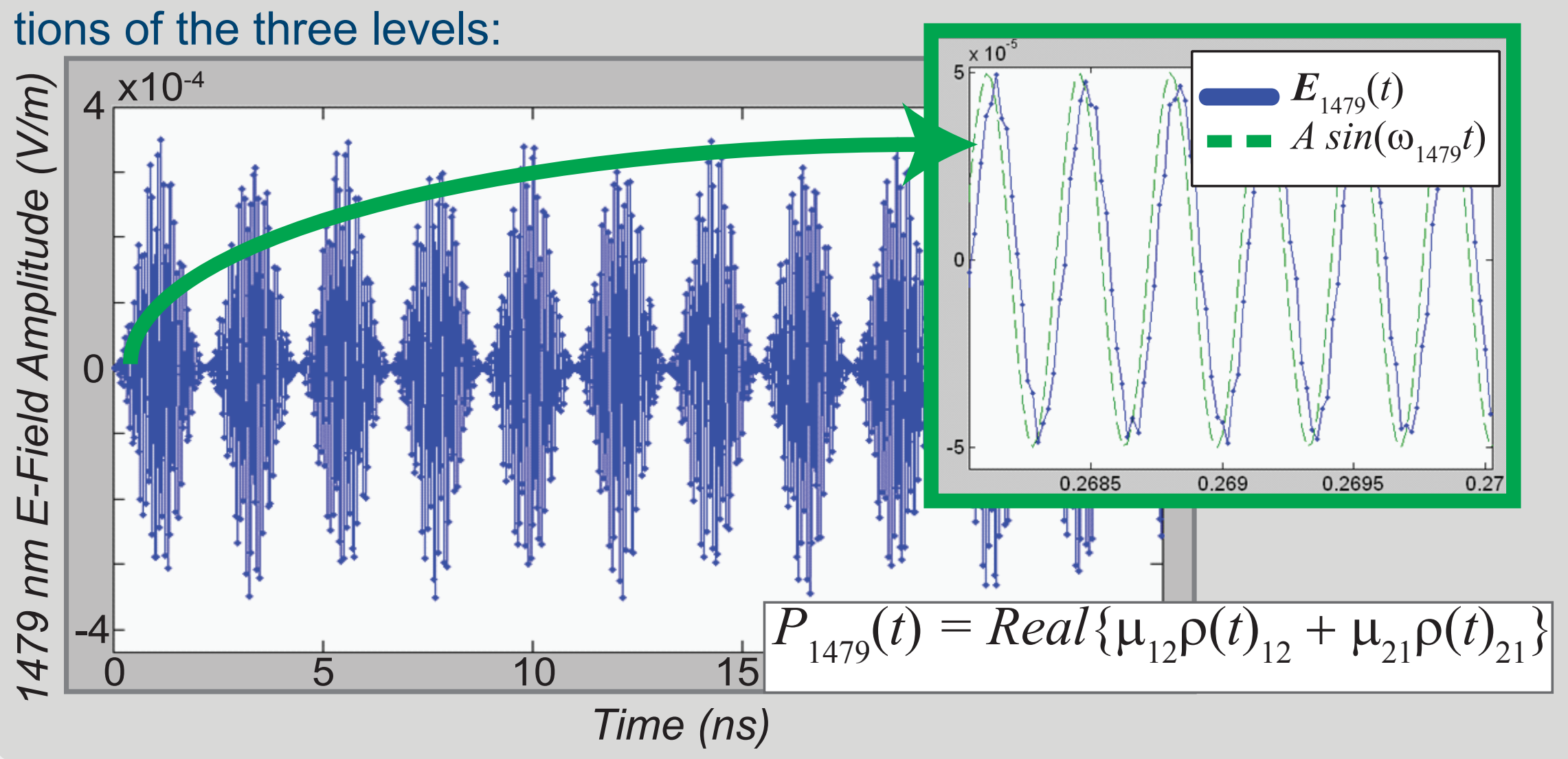


Four-Wave Mixing in Yb Vapor

Simultaneous excitation of the $^1S_0 \rightarrow {}^3D_2$ two-photon transition (808 nm) and the $^1S_0 \rightarrow {}^3P_1$ single-photon transition (556 nm) in Yb can generate a 1479 nm radiation field resonant with the $^3D_2 \rightarrow {}^3P_1$ transition through four-wave mixing.

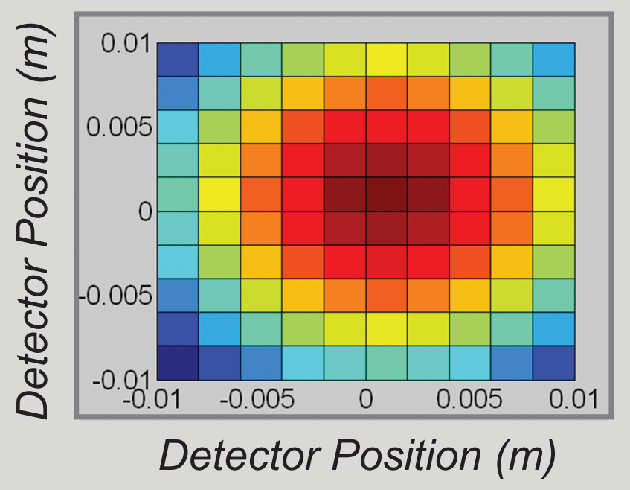
Amplitude Results of Model

Initial evolution of 1479 nm wave from one Yb atom, linearly proportional to the polarization P_{1479} of the $^3P_1 \rightarrow {}^3D_2$ transition. Phase oscillations correspond to 1479nm. Envelope oscillations correspond in time to state populations of the three levels:



$$P_{1479}(t) = Real\{\mu_{12}\rho(t)_{12} + \mu_{21}\rho(t)_{21}\}$$

Directional Results of Model



Relative intensity pattern of 1479 nm signal expected along the direction of laser propagation at a detector placed 3 cm from the LIF region. Dipole moment magnitude is a large source of error in calculating absolute intensity (photon count rate) expected at the detector.

AFOSR Atomic & Molecular Physics Program Review, Arlington, VA, USA, January 5-6, 2012