SCOPE**成果発表会**

11 June 2008

量子縮退原子スピンを用いた全く新しい光の量子もつれ合い状態の生成と制御に関する研究

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Outline

I. Our Approach

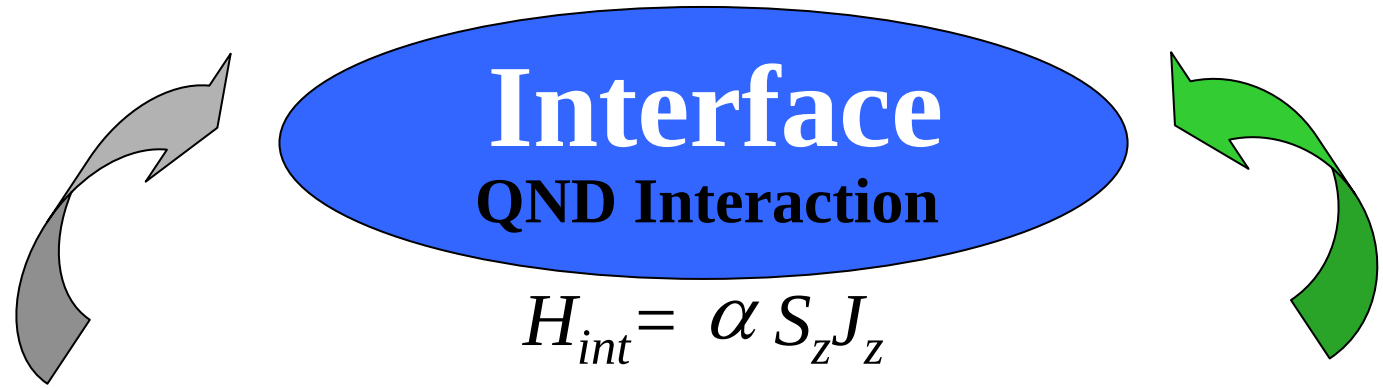
- **QND Interaction of Light Polarization and Atomic Spin**
- **Use of Ytterbium Atomic Spin**

II. Experimental Results

- **Pulsed Polarization Detection System**
- **Realization of Spin QND**

III. Prospects

“Quantum Interface”



“*Communication*”

Light Polarization:
Quantum Stokes Operators

$$J_z = (a_+^\dagger a_+ - a_-^\dagger a_-)/2,$$
$$J_x = (a_+^\dagger a_- + a_-^\dagger a_+)/2,$$
$$J_y = (a_+^\dagger a_- - a_-^\dagger a_+)/2i,$$

$$[J_\lambda, J_\mu] = i\varepsilon_{\lambda\mu\nu} J_\nu$$
$$\lambda,\mu,\nu = x,y,z$$

“*Memory*”

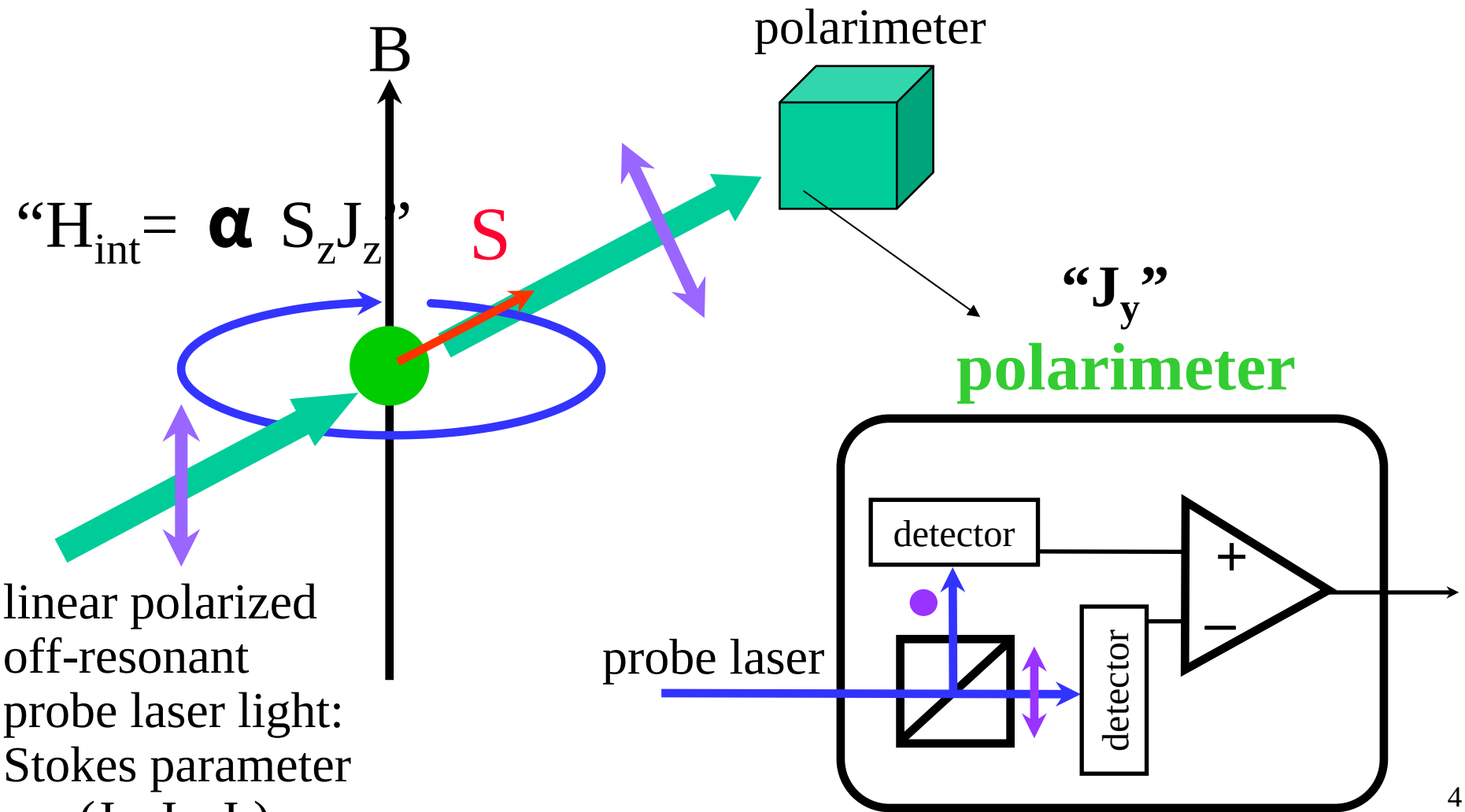
Atoms:
Collective Spin Operators

$$S_X = \sum_i s_x^{(i)}, S_Y = \sum_i s_y^{(i)}, S_Z = \sum_i s_z^{(i)}$$

$$[S_\lambda, S_\mu] = i\varepsilon_{\lambda\mu\nu} S_\nu$$
$$\lambda,\mu,\nu = x,y,z$$

“Faraday Rotation as Spin QND”

Y. Takahashi *et al.*, PRA **60**, 4974, (1999);
A. Kuzmich *et al.*, Europhys. Lett. 42, 481(1998)



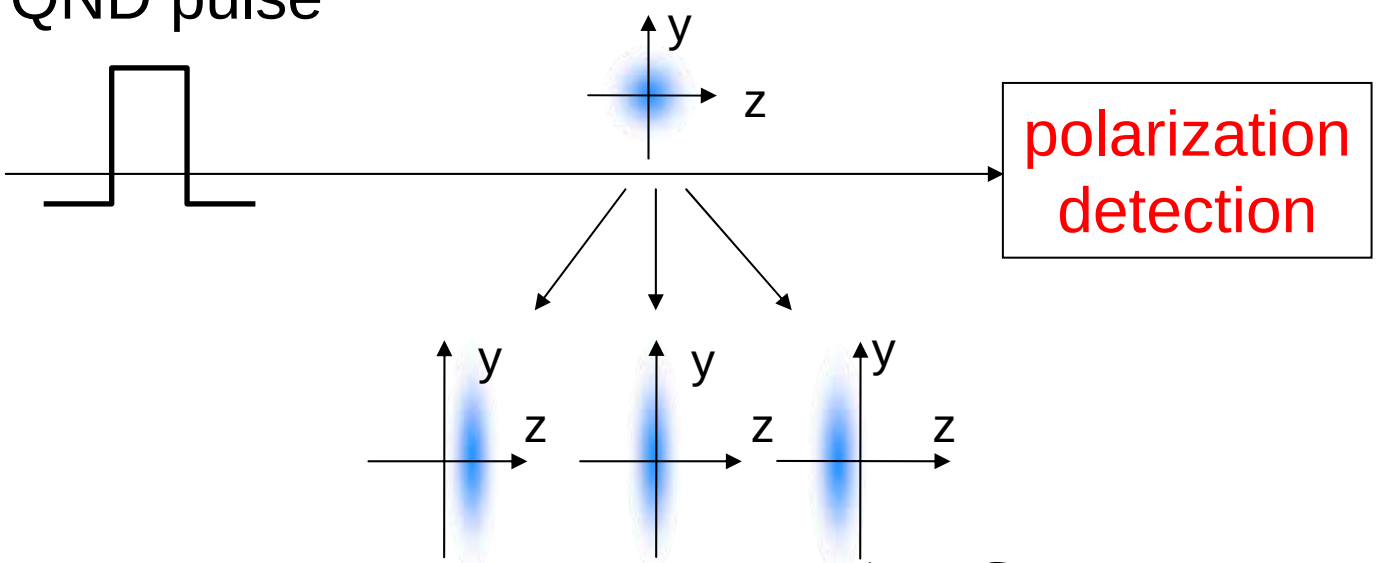
“Spin Squeezing via QND”

Projection of the Result of **QND**Measurement

$S_z(0)$ → $H_{int} = \alpha S_z J_z$ → $S_z(t) = S_z(0)$

$J_y(0)$ → $H_{int} = \alpha S_z J_z$ → $J_y(t)$: **Measurement**

QND pulse



After Projection → $\left\langle \Delta S_z^{\,2} \right\rangle = \frac{1}{1+\kappa^2} \frac{S_x}{2}$

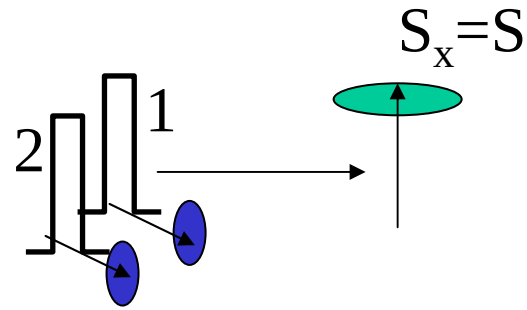
$\kappa = \alpha t \sqrt{SJ}$

“Polarization Entanglement”

Initial state: (t=0)

Spin $\left| S \right\rangle^{in} = \sum c_m \left| S_z=m \right\rangle$

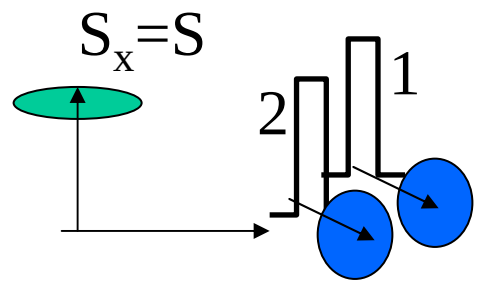
light $\left| J \right\rangle^{in} = \left| J_X=J \right\rangle_1 \left| J_X=J \right\rangle_2$



$$\left|\psi\right\rangle^{out} = \exp(-i\alpha S_z J_z^{(2)} t)\exp(-i\alpha S_z J_z^{(1)} t)\left| S \right\rangle^{in} \left| J \right\rangle^{in}$$

$$= \sum c_m \left| S_z=m \right\rangle \exp(-i\alpha mt J_z^{(1)}) \left| J_X=J \right\rangle_1 \exp(-i\alpha mt J_z^{(2)}) \left| J_X=J \right\rangle_2$$

$$= \sum c_m \left| S_z=m \right\rangle \left| \theta=\alpha mt/2 \right\rangle_1 \left| \theta=\alpha mt/2 \right\rangle_2$$



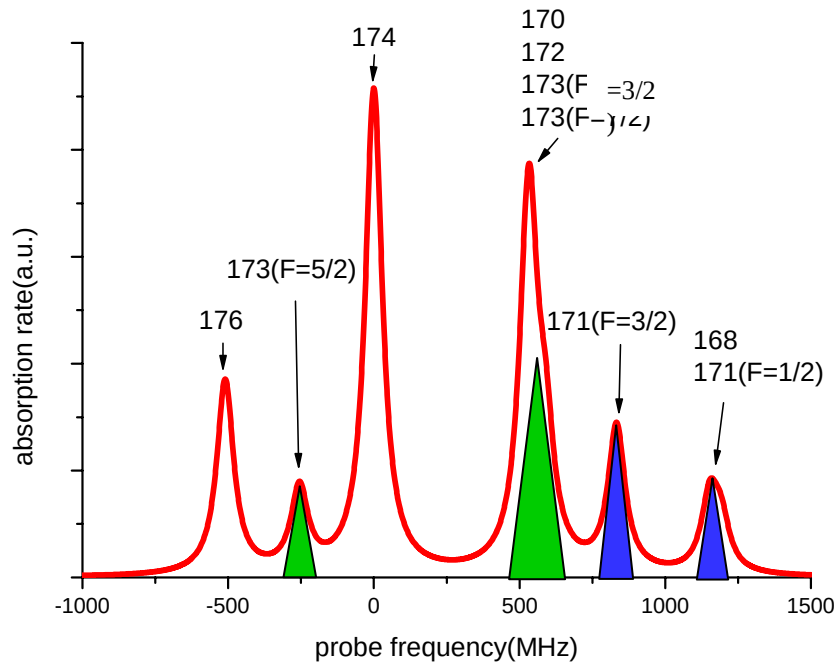
Measuring S_x or S_y

$$\left|\psi\right\rangle^{fin} = \sum c'_m \left| \theta=\alpha mt/2 \right\rangle_1 \left| \theta=\alpha mt/2 \right\rangle_2$$

“Use of Ytterbium Spin”

^{171}Yb atom (I=1/2) & ^{173}Yb atom (I=5/2)

- $^{1}S_0$ state: no electron spin
- No collision at low temperature (Fermion)
- Spin 1/2 (^{171}Yb) :no tensor effect



mass	rate	spin
168	0.13%	0
170	3.05%	0
171	**14.3 %**	**1/2**
172	21.9%	0
173	**16.2 %**	**5/2**
174	31.8%	0
176	12.7%	0

Cooling to Quantum Degeneracy

[T. Fukuhara *et al.*, Phys. Rev. Lett. **98**, 0304012 (2007);JLTP, **148** 441(2007)]

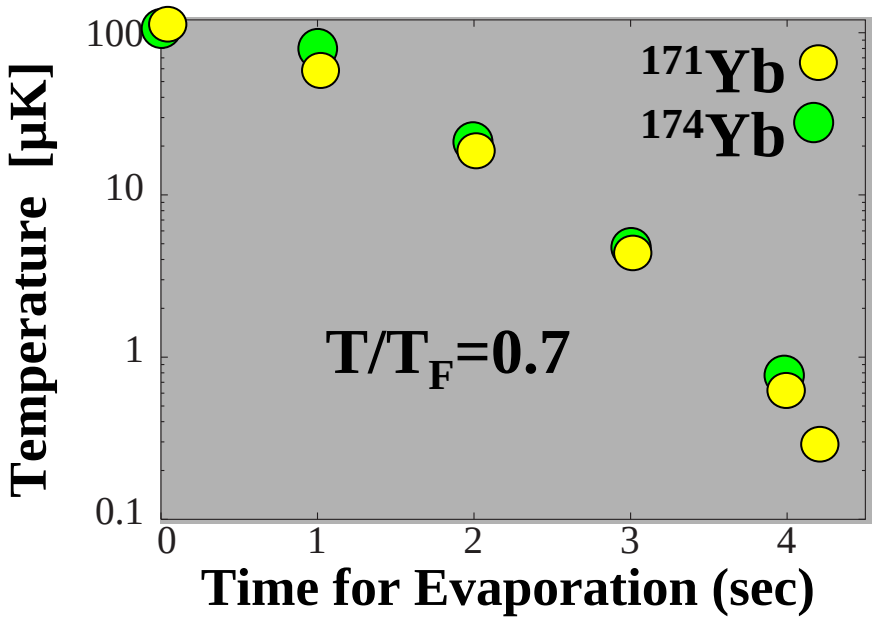
^{171}Yb

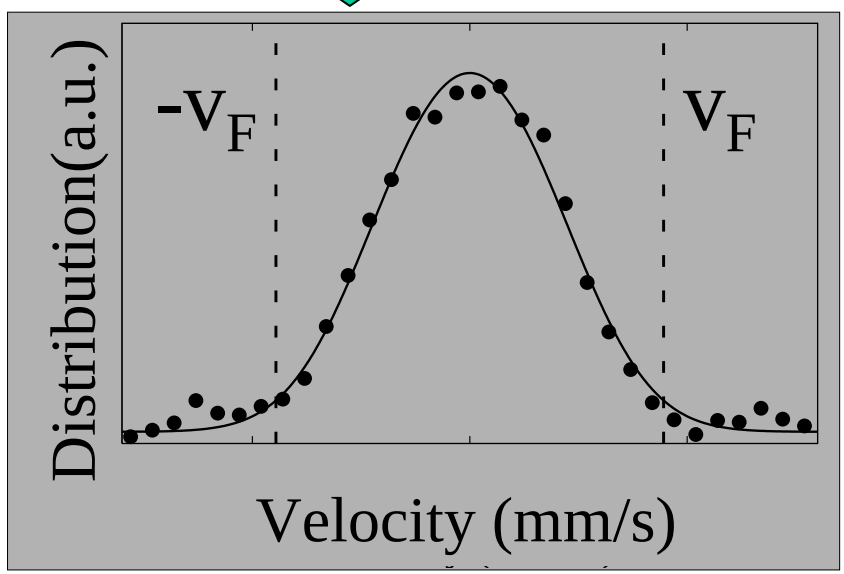
(I=1/2)

^{173}Yb

(I=5/2)

T/T_F=0.37





m_I=

+5/2

+3/2

+1/2

–1/2

–3/2

–5/2

Pulsed Polarization Detection System

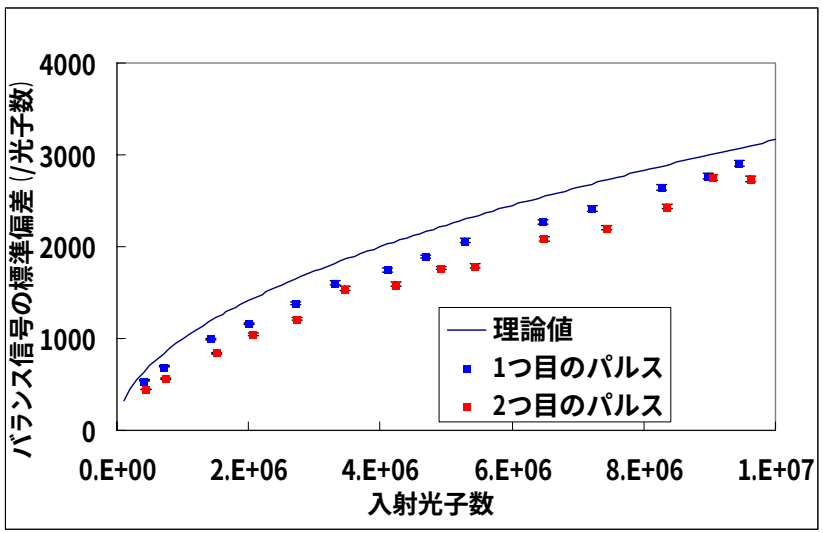
[M. Takeuchi et al., Appl. Phys. B 83, 33(2006)]

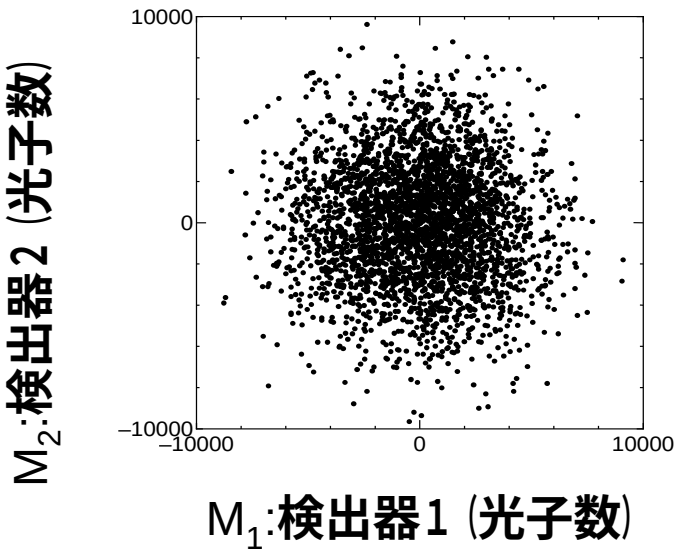
Pulse width 100 ns ~ 400 ns

–Pulse separation > 5 μs

–Narrow bandwidth < 1 MHz

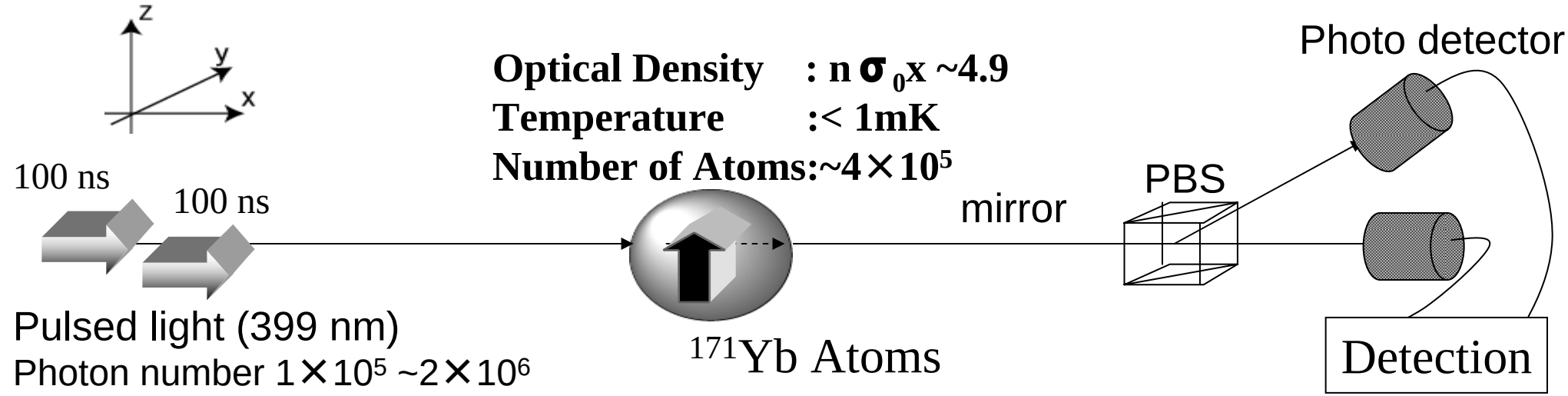
–Tunable to Yb $^1S_0$-$^1P_1$ resonance (399 nm)

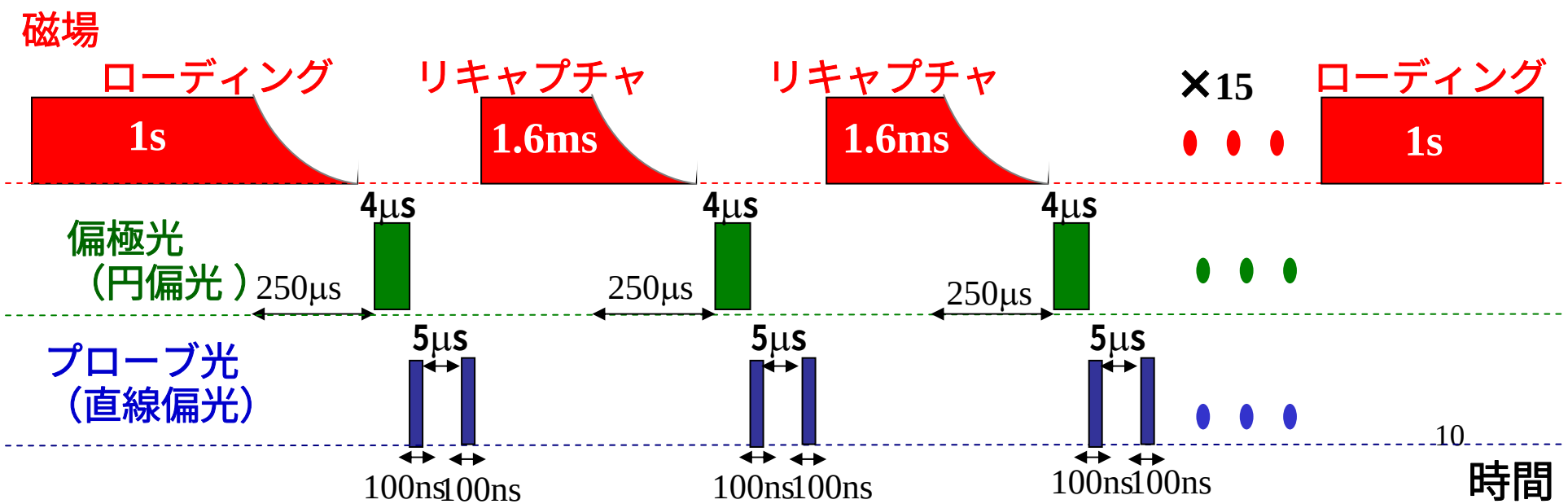




Realization of Spin QND

[T. Takano *et al.*, in preparation]

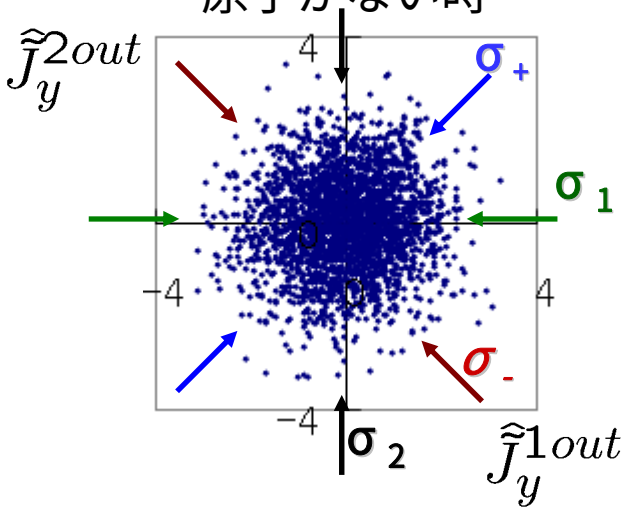




Realization of Spin QND

[T. Takano *et al.*, in preparation]

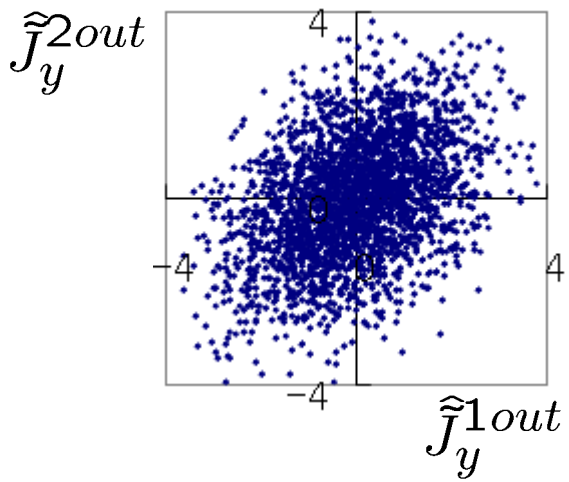
原子がない時



σ_1	0.98
σ_2	0.99
σ_+	1.02
σ_-	0.96

原子がある時

約2500回のデータ点



σ_1	1.26
σ_2	1.29
σ_+	1.51
σ_-	0.99

$$\tilde{S}_x^{out} = \tilde{S}_x^{in}$$

$$\tilde{J}_y^{1out} = \tilde{J}_y^{1in} + \kappa \tilde{S}_x^{in} \qquad \tilde{J}_y^{1out} + \tilde{J}_y^{2out} = \tilde{J}_y^{1in} + \tilde{J}_y^{2in} + 2\kappa \tilde{S}_x^{in}$$

$$\tilde{J}_y^{2out} = \tilde{J}_y^{2in} + \kappa \tilde{S}_x^{in} \qquad \tilde{J}_y^{1out} - \tilde{J}_y^{2out} = \tilde{J}_y^{1in} - \tilde{J}_y^{2in}$$

$$\sigma_1 \equiv \left\langle \Delta \tilde{J}_y^{1out} \right\rangle^2 \qquad \sigma_+ \equiv \left\langle \Delta (\tilde{J}_y^{1out} + \tilde{J}_y^{2out}) \right\rangle^2 / 2$$

$$\sigma_2 \equiv \left\langle \Delta \tilde{J}_y^{2out} \right\rangle^2 \qquad \sigma_- \equiv \left\langle \Delta (\tilde{J}_y^{1out} - \tilde{J}_y^{2out}) \right\rangle^2 / 2$$

Realization of Spin QND

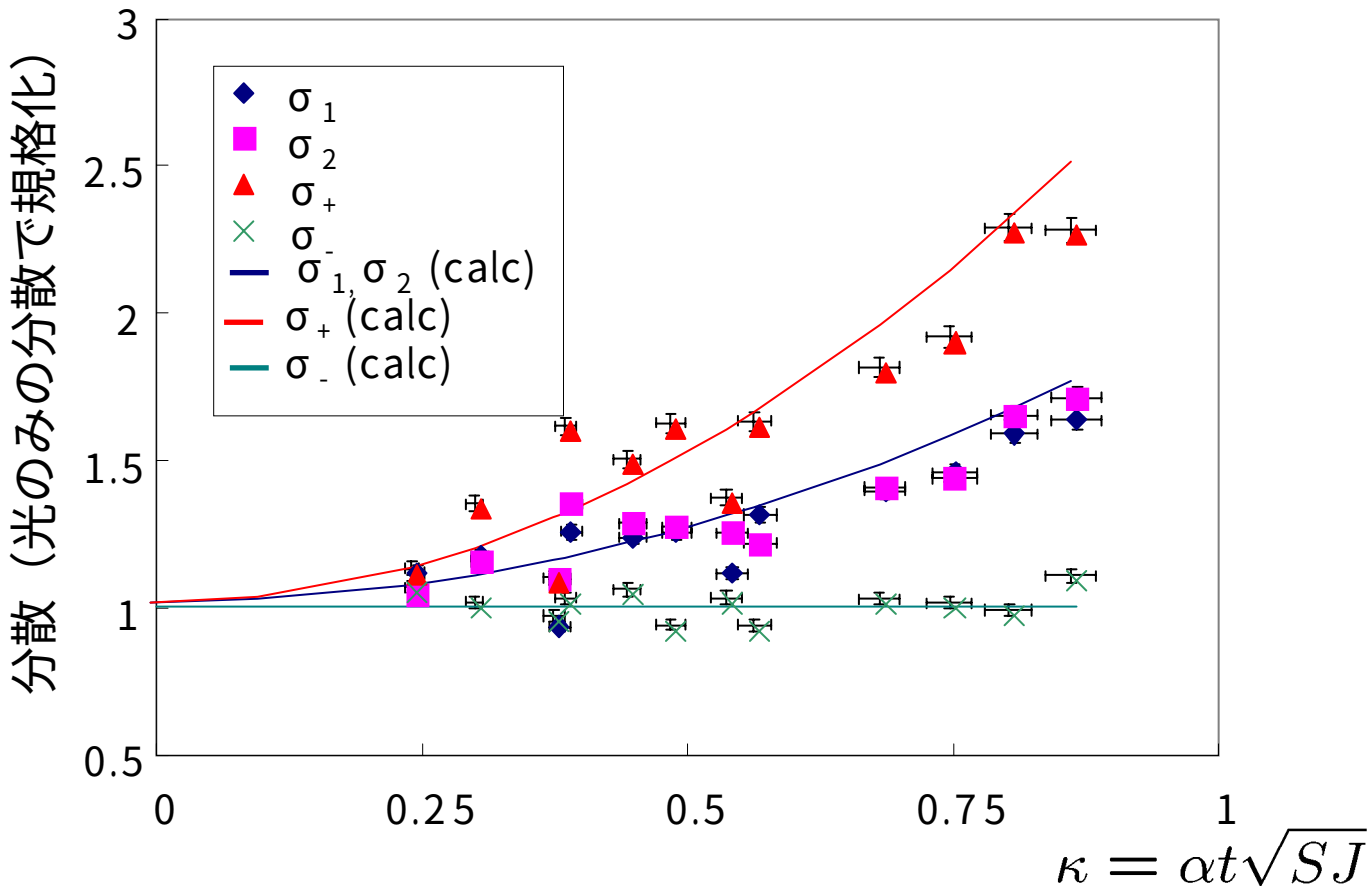
[T. Takano *et al.*, in preparation]

$$\sigma_{1,2} = 1 + \kappa^2$$

$$\sigma_+ = 1 + 2\kappa^2$$

$$\sigma_- = 1$$

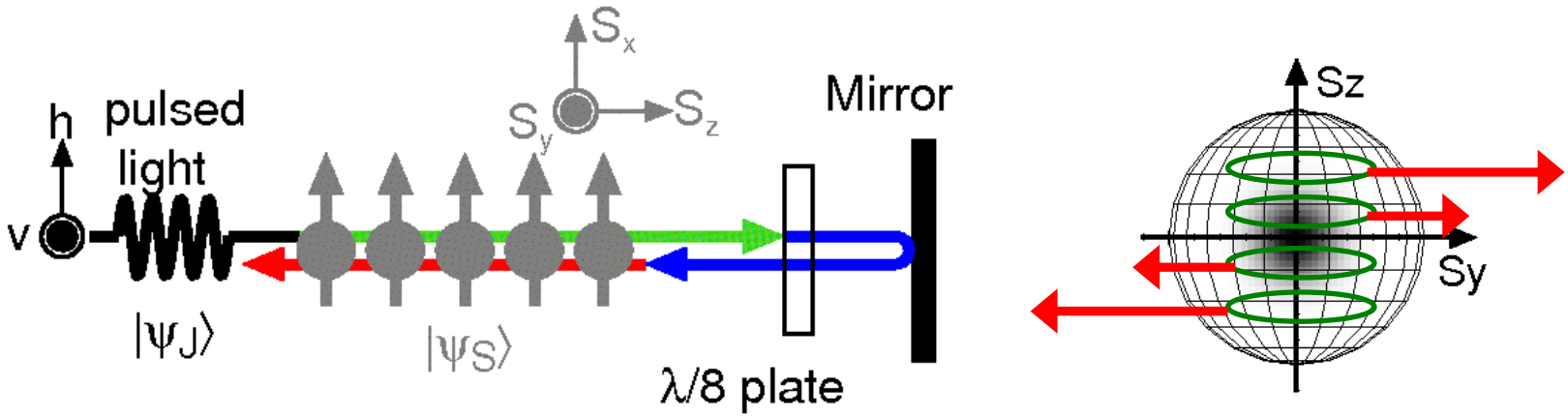
$$\kappa = \alpha t \sqrt{SJ}$$



Future Prospects

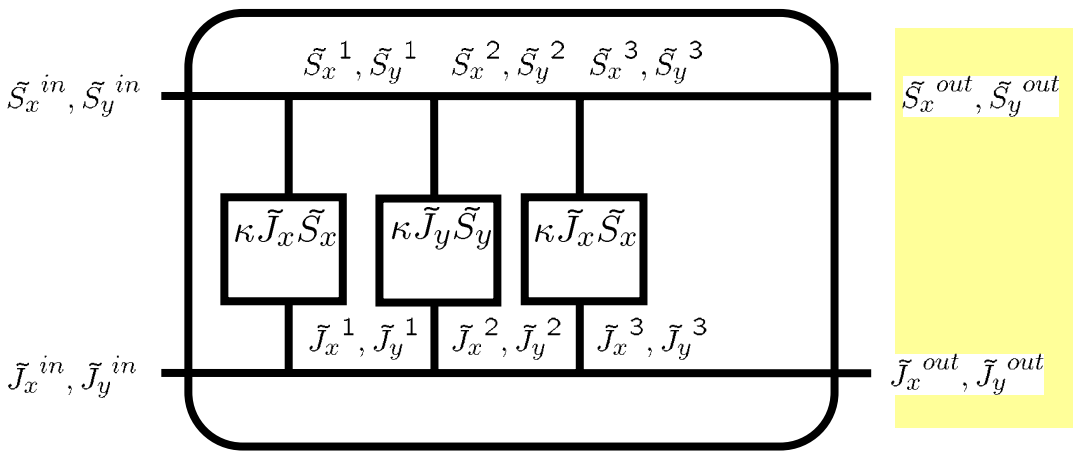
Spin Squeezing via One-Axis Twisting by Coherent Light

[M. Takeuchi, *et al.*, Phys. Rev. Lett. 94, 023003(2005)]



Quantum Swapping Between Light and Atomic Spin

[T. Takano, *et al.*, Phys. Rev. A. Rapid Communication, (2008)]



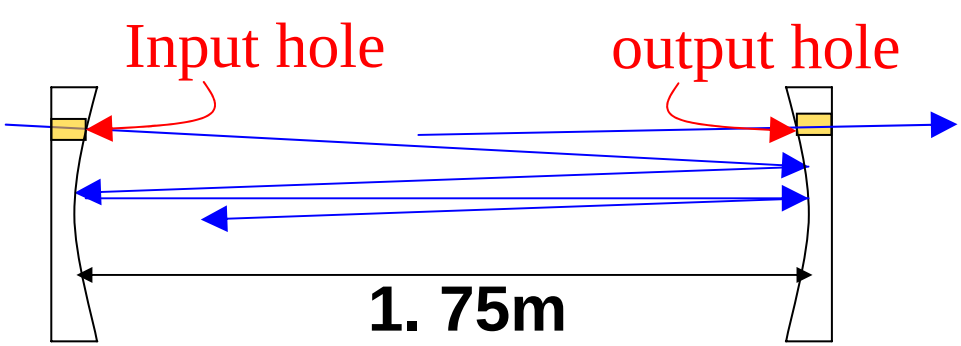
$$\tilde{S}_x^{out} = \tilde{J}_y^{in}, \tilde{S}_y^{out} = -\tilde{J}_x^{in}$$

$$\tilde{J}_x^{out} = \tilde{S}_y^{in}, \tilde{J}_y^{out} = -\tilde{S}_x^{in}$$

$$\text{for } \kappa = \alpha t\sqrt{SJ} = 1$$

Future Prospects

Polarization Measurement with Delay Line

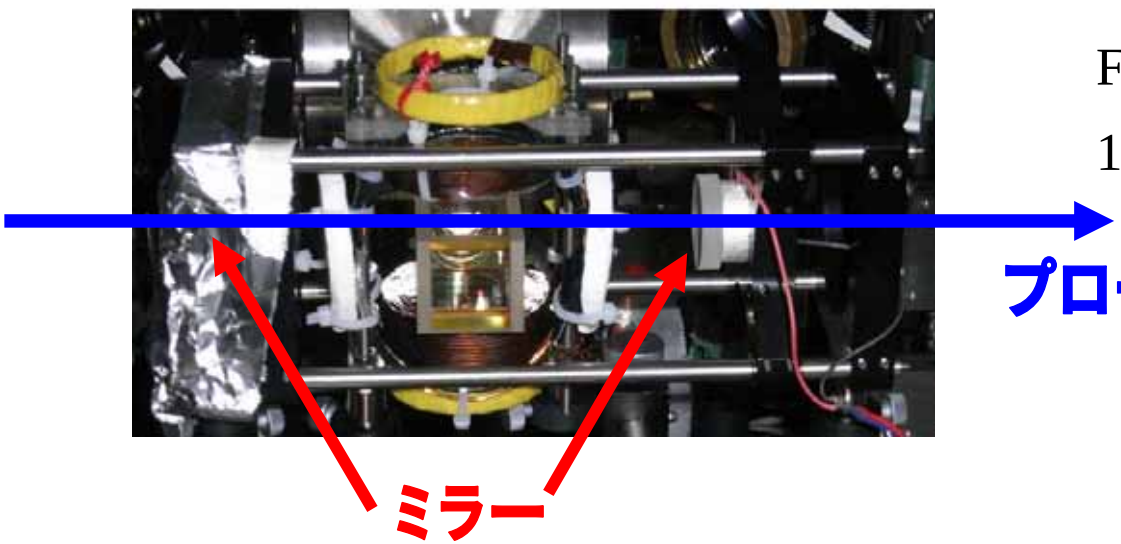


175 ns Delay Time

Shot-noise limited

observation of Faraday rotation

Cavity-enhancement of Spin QND



Faraday rotation angle: $\theta_C = \theta \times 2F/\pi$

110 mrad Faraday rotation observed

Summary

Cooling to Quantum Degeneracy: $T/T_F<1$

Realization of Spin QND Measurement of ^{171}Yb

Nuclear spin I=1/2

Proposals

Spin squeezing with coherent light

Quantum swapping between light and spin

Cavity-enhancement of spin QND interaction