

Quantum Degenerate Gases of Ytterbium Atoms

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Group Members



Wasan

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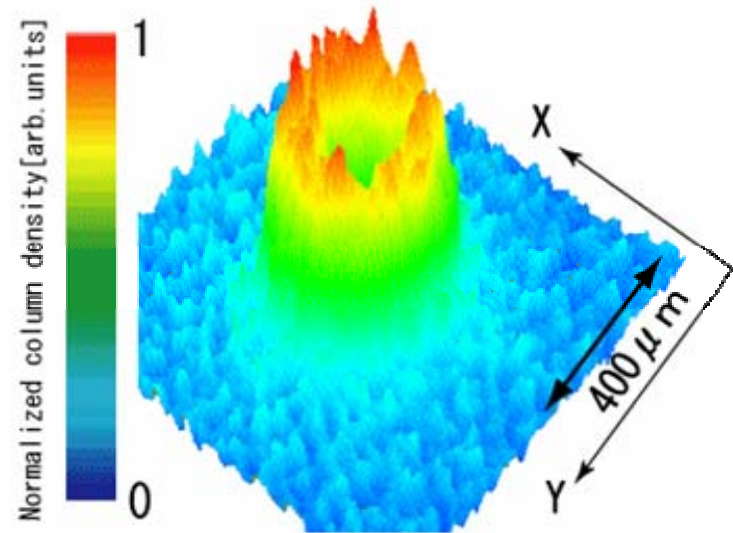
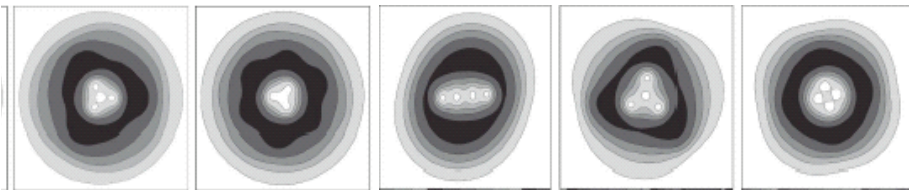
multiply charged quantized vortex

Collaboration with prof. M. Kumakura (Fukui), Mr. H. Yasuda (Kyoto), Dr. Isoshima (Kyoto)

“ ^{87}Rb BEC in $F = 2, m_F = 2$
state”
magnetic field reversal :
 $0.4 \text{ G} \rightarrow -0.4 \text{ G} \quad (3 \text{ ms})$



Quadruply Charged Quantized Vortex



axial image (TOF = 25 ms)

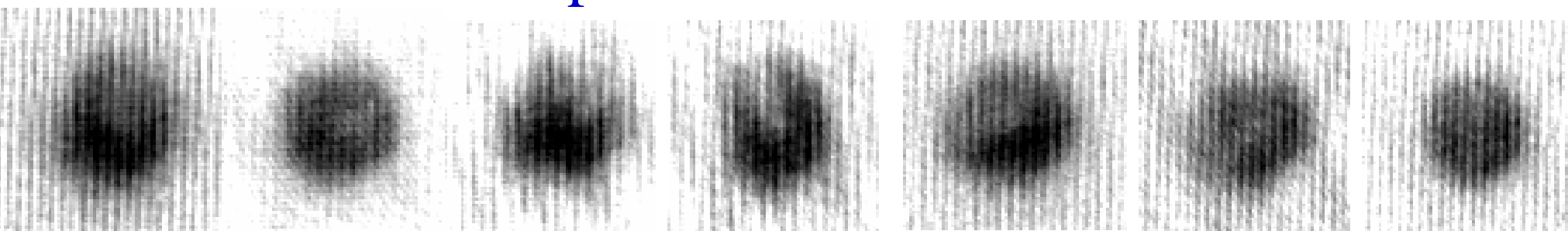
[M. Kumakura et al, PRA73, 063605 (2006)]

Y.Kawaguchi and T.Ohmi, Phys.Rev.A 70, 043610(2004)

multiply charged quantized vortex

vortex deformation

Experimental results



3.0 ms

4.0 ms

4.3 ms

4.5 ms

5.5 ms

6.5 ms

7.5 ms

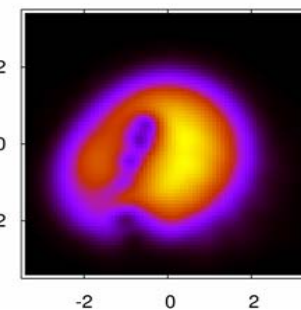
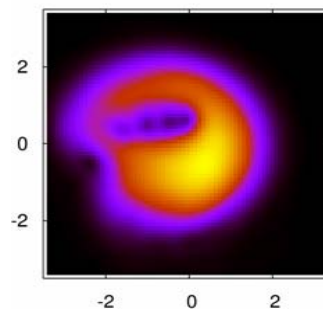
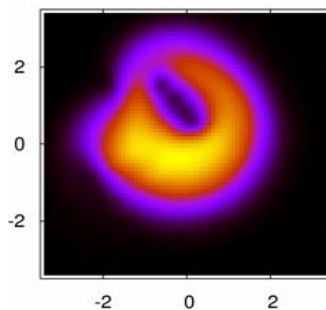
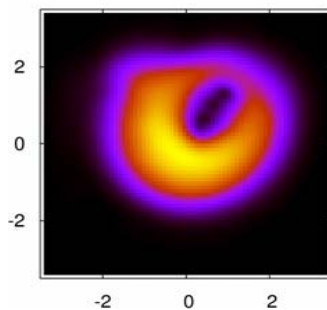
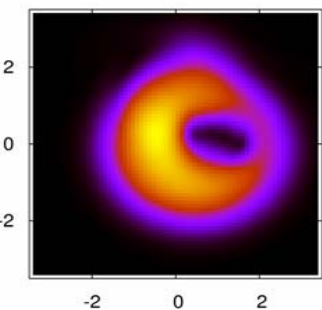
3.500 ms

4.000 ms

4.500 ms

5.000 ms

5.500 ms



3D calculation [T.Isoshima]

Atomic BEC and Fermi Degeneracy

1995 ^{87}Rb , ^{23}Na , ^7Li

1998 ^1H

1999 ^{40}K

2000 ^{85}Rb

2001 ^{41}K $^4\text{He}^*$ ^6Li

2003 ^{133}Cs ^{174}Yb

2005 ^{52}Cr

PERIODIC TABLE

Atomic Properties of the Elements

NIST

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

18
VIIIA

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

Ytterbium atom

$R_{\infty}c$ 3.289 842 × 10¹⁵ Hz
 $R_{\infty}hc$ 13.6057 eV
Boltzmann constant k 1.3807 × 10⁻²³ J K⁻¹

Physics Laboratory physics.nist.gov
Standard Reference Data Group www.nist.gov/srd

Group 1 IA	1 ¹ H Hydrogen 1.00794 1s 13.5984	2 IIA
2	3 ² Li Lithium 6.941 1s ² 2s 5.3917	4 ¹ Be Beryllium 9.012182 1s ² 2s ² 9.3227
3	11 ² Na Sodium 22.989770 [Ne]3s 5.1391	12 ¹ Mg Magnesium 24.3050 [Ne]3s ² 7.6462
4	19 ² K Potassium 39.0983 [Ar]4s 4.3407	20 ¹ Ca Calcium 40.078 [Ar]4s ² 6.1132
5	37 ² Rb Rubidium 85.4678 [Kr]5s 4.1771	38 ¹ Sr Strontium 87.62 [Kr]5s ² 6.5949
6	55 ² Cs Cesium 132.90545 [Xe]6s 3.8939	56 ¹ Ba Barium 137.327 [Xe]6s ² 5.2117
7	87 ² Fr Francium (223) [Rn]7s 4.0727	88 ¹ Ra Radium (226) [Rn]7s ² 5.2784

3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9	10	11 IB	12 IIB
21 ² Sc Scandium 44.955910 [Ar]3d ¹ 4s ² 6.5615	22 ² Ti Titanium 47.867 [Ar]3d ² 4s ² 6.8281	23 ² V Vanadium 50.9415 [Ar]3d ³ 4s ² 6.7462	24 ¹ Cr Chromium 51.9961 [Ar]3d ⁵ 4s 6.7665	25 ⁶ Mn Manganese 54.938049 [Ar]3d ⁵ 4s ² 7.4340	26 ⁶ Fe Iron 55.845 [Ar]3d ⁶ 4s ² 7.9024	27 ⁴ Co Cobalt 58.933200 [Ar]3d ⁷ 4s ² 7.8810	28 ⁴ Ni Nickel 58.6934 [Ar]3d ⁸ 4s ² 7.6398	29 ² Cu Copper 63.546 [Ar]3d ¹⁰ 4s 7.7264	30 ¹ Zn Zinc 65.409 [Ar]3d ¹⁰ 4s ² 9.942
39 ² Y Yttrium 88.90585 [Kr]4d ¹ 5s ² 6.2173	40 ² Zr Zirconium 91.224 [Kr]4d ² 5s ² 6.6339	41 ¹ Nb Niobium 92.90638 [Kr]4d ⁴ 5s 7.0924	42 ⁶ Mo Molybdenum 95.94 [Kr]4d ⁵ 5s 7.28	43 ⁶ Tc Technetium (98) [Kr]4d ⁵ 5s ² 7.28	44 ⁶ Ru Ruthenium 101.07 [Kr]4d ⁷ 5s 7.3605	45 ⁴ Rh Rhodium 102.90550 [Kr]4d ⁸ 5s 7.4589	46 ¹ Pd Palladium 106.42 [Kr]4d ¹⁰ 8.3389	47 ² Ag Silver 107.8682 [Kr]4d ¹⁰ 5s 7.5762	48 ¹ Cd Cadmium 112.411 [Kr]4d ¹⁰ 5s ² 5.7864
72 ³ Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ² 6.8251	73 ⁴ Ta Tantalum 180.9479 [Xe]4f ¹⁴ 5d ³ 6s ² 7.5496	74 ³ W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ² 7.8640	75 ⁶ Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ² 7.8335	76 ⁶ Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ² 8.4382	77 ⁴ Ir Iridium 192.217 [Xe]4f ¹⁴ 5d ⁷ 6s ² 8.9670	78 ³ Pt Platinum 195.078 [Xe]4f ¹⁴ 5d ⁸ 6s 8.9588	79 ² Au Gold 196.96655 [Xe]4f ¹⁴ 5d ¹⁰ 6s 9.2255	80 ¹ Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375	81 ² Tl Thallium 204.3833 [Hg]6p 6.1082
104 ³ Rf Rutherfordium (261) [Rn]5f ¹⁴ 6d ² 7s ² 6.0 ?	105 ³ Db Dubnium (262)	106 ³ Sg Seaborgium (266)	107 ³ Bh Bohrium (264)	108 ³ Hs Hassium (277)	109 ³ Mt Meitnerium (268)	110 ³ Uun Ununnilium (281)	111 ³ Uuu Unununium (272)	112 ³ Uub Ununbium (285)	114 ³ Uuq Ununquadium (289)

13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
5 ² B Boron 10.811 1s ² 2s ² 2p 8.2980	6 ³ C Carbon 12.0107 1s ² 2s ² 2p ² 11.2603	7 ⁴ N Nitrogen 14.0067 1s ² 2s ² 2p ³ 14.5341	8 ³ O Oxygen 15.9994 1s ² 2s ² 2p ⁴ 13.6181	9 ² F Fluorine 18.9984032 1s ² 2s ² 2p ⁵ 17.4228	10 ¹ Ne Neon 20.1797 1s ² 2s ² 2p ⁶ 21.5645
13 ² Al Aluminum 26.981538 [Ne]3s ² 3p 5.9858	14 ³ Si Silicon 28.0855 [Ne]3s ² 3p ² 8.1517	15 ⁴ P Phosphorus 30.973761 [Ne]3s ² 3p ³ 10.4867	16 ³ S Sulfur 32.065 [Ne]3s ² 3p ⁴ 10.3600	17 ² Cl Chlorine 35.453 [Ne]3s ² 3p ⁵ 12.9676	18 ¹ Ar Argon 39.948 [Ne]3s ² 3p ⁶ 15.7596
31 ² Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p 5.9993	32 ² Ge Germanium 72.64 [Ar]3d ¹⁰ 4s ² 4p ² 7.8994	33 ⁴ As Arsenic 74.92160 [Ar]3d ¹⁰ 4s ² 4p ³ 9.7886	34 ² Se Selenium 78.96 [Ar]3d ¹⁰ 4s ² 4p ⁴ 9.7524	35 ² Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵ 11.8138	36 ¹ Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶ 13.9996
49 ² In Indium 114.818 [Kr]4d ¹⁰ 5s ² 5p 5.7864	50 ² Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 5p ² 7.3439	51 ⁴ Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 5p ³ 8.6084	52 ² Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 5p ⁴ 9.0096	53 ² I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 5p ⁵ 10.4513	54 ¹ Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 5p ⁶ 12.1298
81 ² Tl Thallium 204.3833 [Hg]6p 6.1082	82 ³ Pb Lead 207.2 [Hg]6p ² 7.4167	83 ⁴ Bi Bismuth 208.98038 [Hg]6p ³ 7.2855	84 ³ Po Polonium (209) [Hg]6p ⁴ 8.414	85 ² At Astatine (210) [Hg]6p ⁵ 8.414	86 ¹ Rn Radon (222) [Hg]6p ⁶ 10.7485
			116 ³ Uuh Ununhexium (289)		

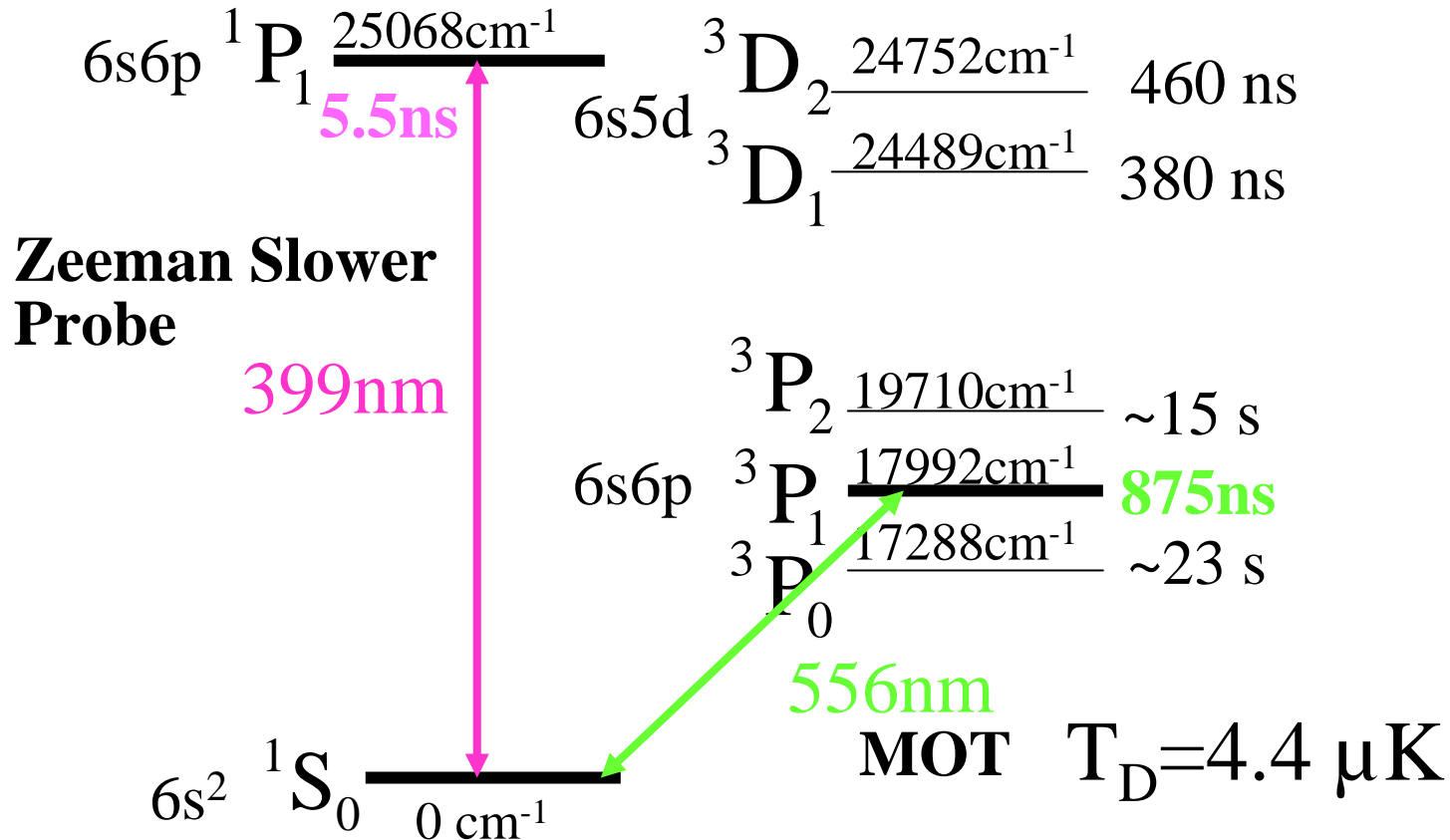
Atomic Number: 58
Ground-state Level: 1G₄
Symbol: Ce
Name: Cerium
Atomic Weight: 140.116
Ground-state Configuration: [Xe]4f¹5d¹6s²
Ionization Energy (eV): 5.5387

57 ² D _{3/2} Lanthanum 138.9055 [Xe]5d ¹ 6s ² 5.5769	58 ¹ G ₄ Cerium 140.116 [Xe]4f ¹ 5d ¹ 6s ² 5.5387	59 ⁴ F _{3/2} Praseodymium 140.90765 [Xe]4f ³ 6s 5.473	60 ⁵ I ₄ Neodymium 144.24 [Xe]4f ⁴ 6s ² 5.5250	61 ⁶ H _{3/2} Promethium (145) [Xe]4f ⁵ 6s ² 5.562	62 ⁷ F ₀ Samarium 150.36 [Xe]4f ⁶ 6s ² 5.6437	63 ⁸ S _{7/2} Europium 151.964 [Xe]4f ⁷ 6s ² 5.6704	64 ⁹ D ₂ Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ² 6.1498	65 ⁶ H _{1/2} Terbium 158.92534 [Xe]4f ⁹ 6s ² 5.8638	66 ⁵ I ₈ Dysprosium 162.500 [Xe]4f ¹⁰ 6s ² 5.9389	67 ⁴ F _{3/2} Holmium 164.93032 [Xe]4f ¹¹ 6s ² 6.0215	68 ³ H ₈ Erbium 167.259 [Xe]4f ¹² 6s ² 6.1077	69 ² F _{7/2} Thulium 168.93421 [Xe]4f ¹³ 6s ² 6.1843	70 ¹ S ₀ Ytterbium 173.04 [Xe]4f ¹⁴ 6s ² 6.2542	71 ² D _{3/2} Lutetium 174.967 [Xe]4f ¹⁴ 5d ¹ 6s ² 5.4259
89 ² D _{3/2} Actinium (227) [Rn]6d ¹ 7s ² 5.17	90 ³ F ₂ Thorium 232.0381 [Rn]6d ² 7s ² 6.3067	91 ⁴ K _{11/2} Protactinium 231.03588 [Rn]5f ¹ 6d ² 7s ² 5.89	92 ⁵ L ₆ Uranium 238.02891 [Rn]5f ³ 6d ¹ 7s ² 6.1941	93 ⁶ L _{11/2} Neptunium (237) [Rn]5f ⁴ 6d ¹ 7s ² 6.2657	94 ⁷ F ₀ Plutonium (244) [Rn]5f ⁶ 7s ² 6.0260	95 ⁸ S _{7/2} Americium (243) [Rn]5f ⁷ 7s ² 5.9738	96 ⁹ D ₂ Curium (247) [Rn]5f ⁸ 6d ¹ 7s ² 5.9914	97 ⁶ H _{1/2} Berkelium (247) [Rn]5f ⁹ 7s ² 6.1979	98 ⁵ I ₈ Californium (251) [Rn]5f ¹⁰ 7s ² 6.2817	99 ⁴ F _{3/2} Einsteinium (252) [Rn]5f ¹¹ 7s ² 6.42	100 ³ H ₈ Fermium (257) [Rn]5f ¹² 7s ² 6.50	101 ² F _{7/2} Mendelevium (258) [Rn]5f ¹³ 7s ² 6.58	102 ¹ S ₀ Nobelium (259) [Rn]5f ¹⁴ 7s ² 6.65	103 ² P _{1/2} Lawrencium (262) [Rn]5f ¹⁴ 7s ² 7p ¹ 4.9 ?

[†]Based upon ¹²C. () indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

Energy Levels of Yb Atom



Two-Electron Atom: (Xe) $4f^{14} 6s^2$

Unique Property of Yb Atom

A Variety of Isotopes

Boson: ^{168}Yb (0.13%), ^{170}Yb (3.05%), ^{172}Yb (21.9%),
(even mass number) ^{174}Yb (31.8%), ^{176}Yb (12.7%)

Fermion: ^{171}Yb (14.3%, $I=1/2$), ^{173}Yb (16.2%, $I=5/2$)
(odd mass number)

Various Quantum Degenerate Gases

BEC: ^{168}Yb , ^{170}Yb , ^{172}Yb , ^{174}Yb , ^{176}Yb

Fermi Degeneracy: ^{171}Yb , ^{173}Yb

Various Mixtures of BEC and FD

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Various Quantum Degenerate Gases

BEC: ^{168}Yb , ^{170}Yb , ^{172}Yb , ^{174}Yb , ^{176}Yb

Fermi Degeneracy: ^{171}Yb , ^{173}Yb

Various Mixtures of BEC and FD

Stability analysis of n-component BEC [D. Roberts and M. Ueda, PRA73 053611 (2006)]

Formation of Quantum Degenerate Gas

^{174}Yb (31.8%)

Boson, $I=0$

^{170}Yb (3.05%)

Boson, $I=0$

^{176}Yb (12.7%)

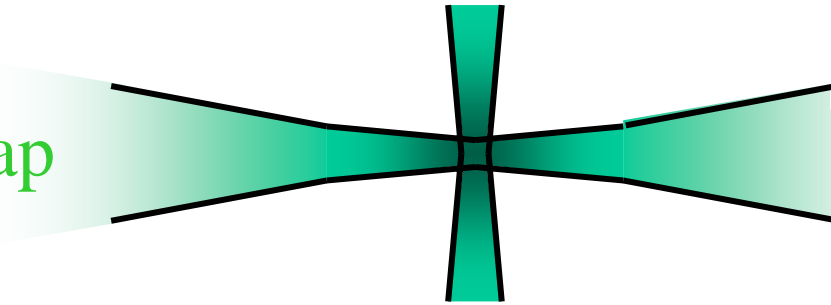
Boson, $I=0$

^{173}Yb (16.2%)

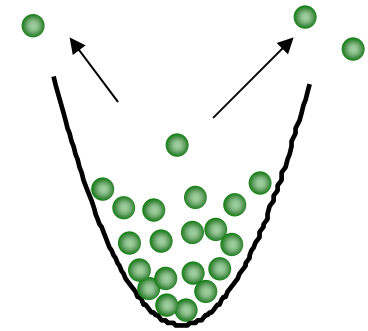
Fermion, $I=5/2$

Experimental Setup

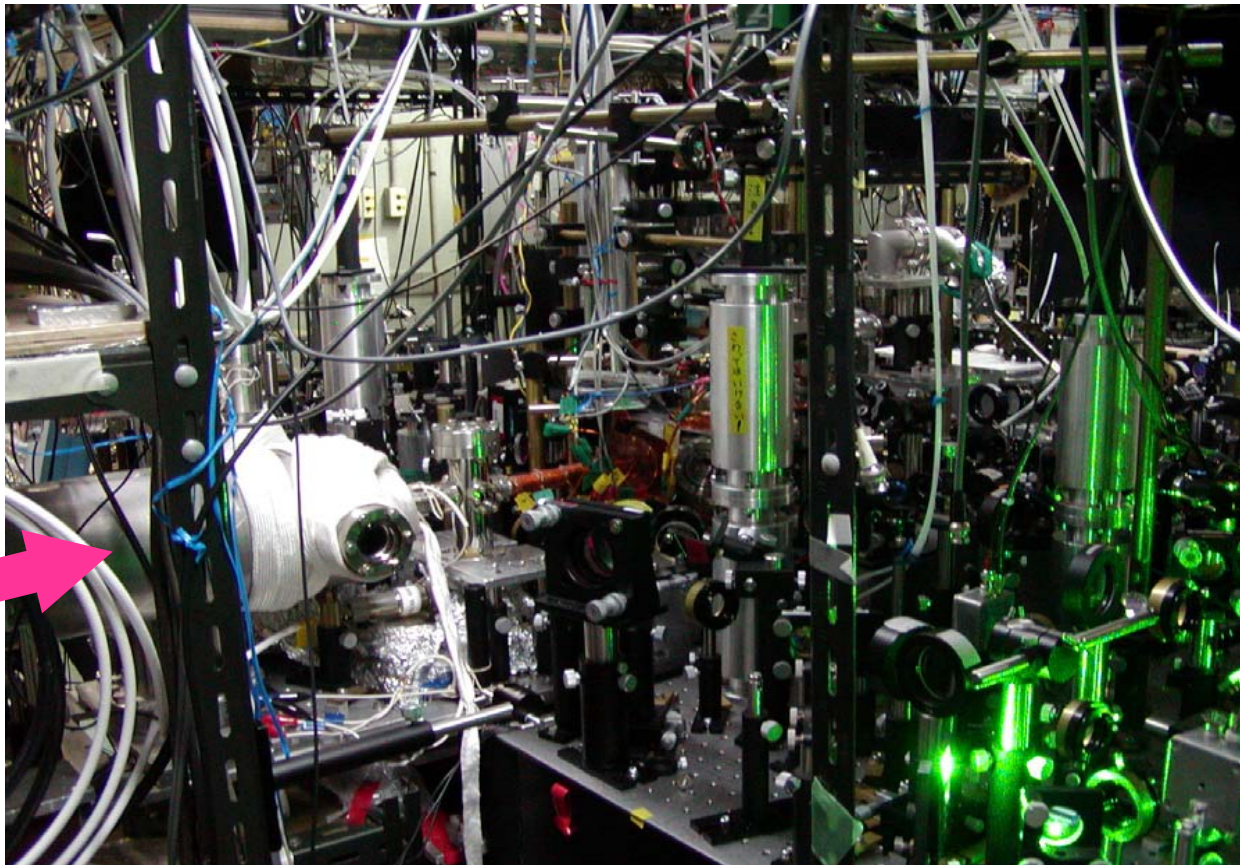
Optical Trap



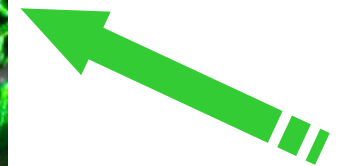
g



Atomic Beam



Optical Trapping
Beams (532 nm)



Formation of Quantum Degenerate Gas

^{174}Yb (31.8%)

Boson, $I=0$

^{170}Yb (3.05%)

Boson, $I=0$

^{176}Yb (12.7%)

Boson, $I=0$

^{173}Yb (16.2%)

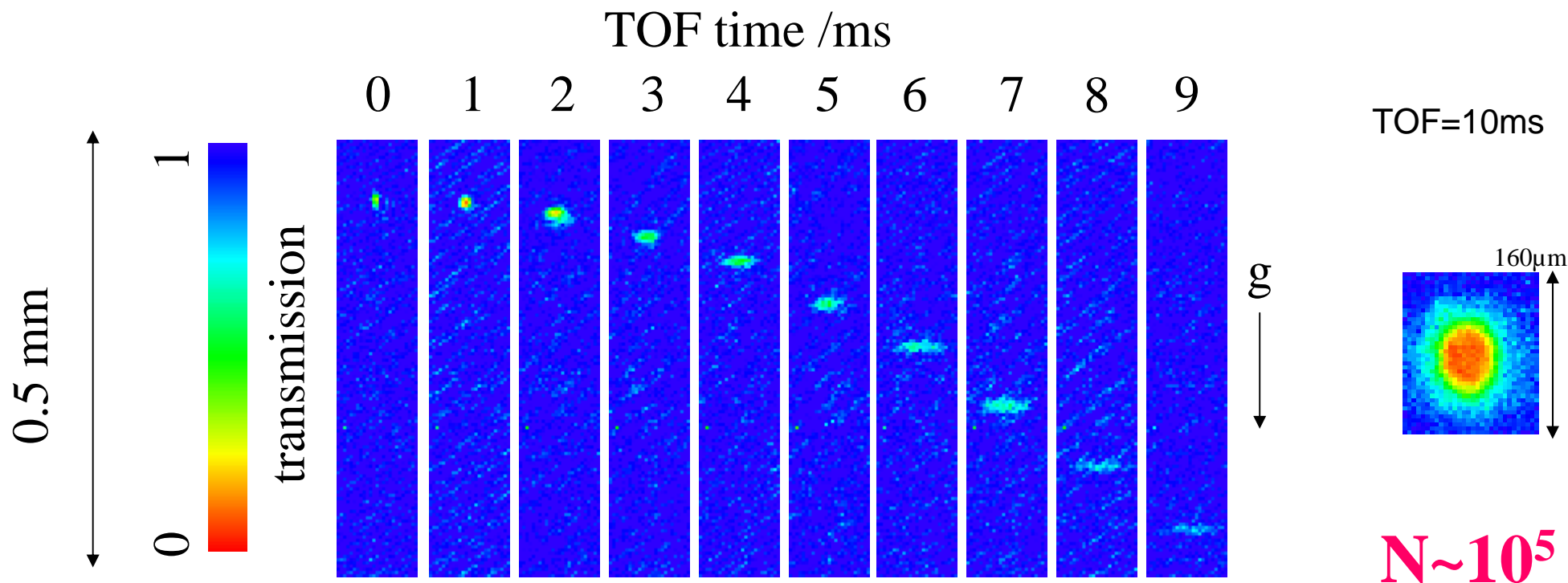
Fermion, $I=5/2$

^{174}Yb BEC

^{174}Yb (31.8%)

BEC $N \sim 10^4$

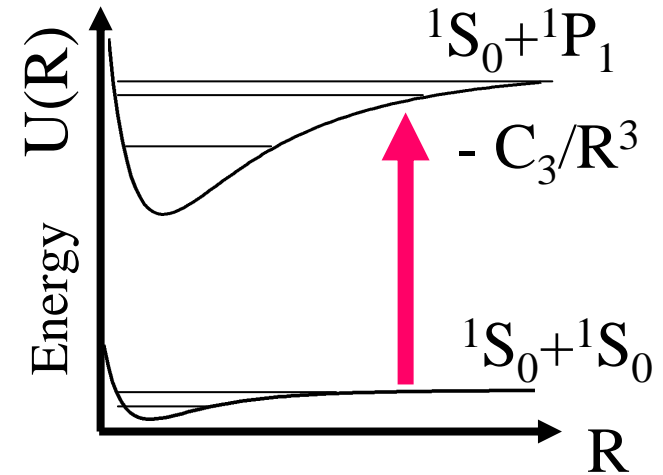
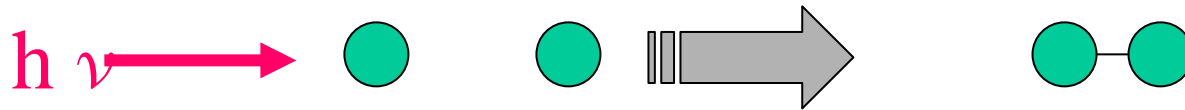
[Y. Takasu et al, PRL 91 040404(2003)]



Quick Formation of BEC: $t \sim 15$ seconds

^{174}Yb : determination of scattering length

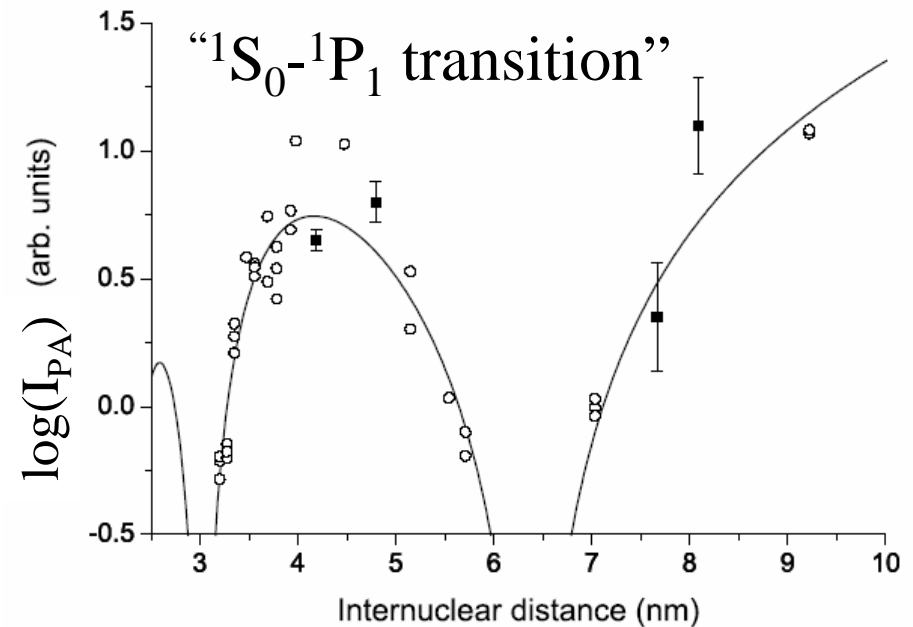
Photo-Association Spectroscopy



$$I_{\text{PA}}(\Delta) \propto \frac{|\Psi_g(R)|^2}{\sqrt{\Delta}} \quad \frac{C_3}{R^3} = \hbar\Delta$$

Scattering wavefunction

Julienne, *J. Res. NIST.* **101**, 487 (1996).



$$\longrightarrow a = 5.5 \text{ nm} \pm 0.2 \text{ nm}$$

Formation of Quantum Degenerate Gas

^{174}Yb (31.8%)

Boson, $I=0$

^{170}Yb (3.05%)

Boson, $I=0$

^{176}Yb (12.7%)

Boson, $I=0$

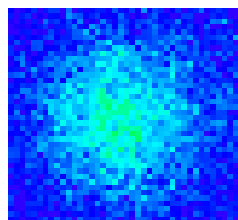
^{173}Yb (16.2%)

Fermion, $I=5/2$

^{170}Yb BEC

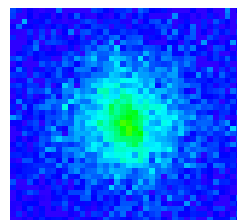
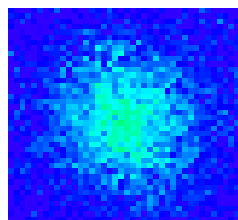
^{170}Yb (3.05%)

high ← Potential depth → low

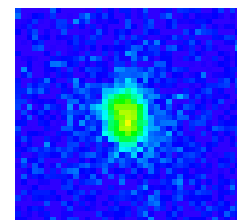
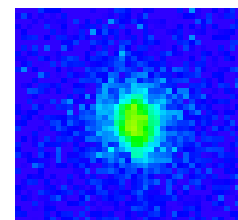


TOF=10ms

thermal

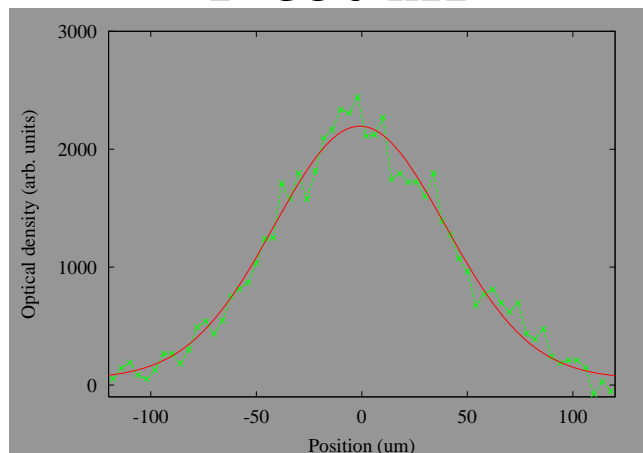


bimodal

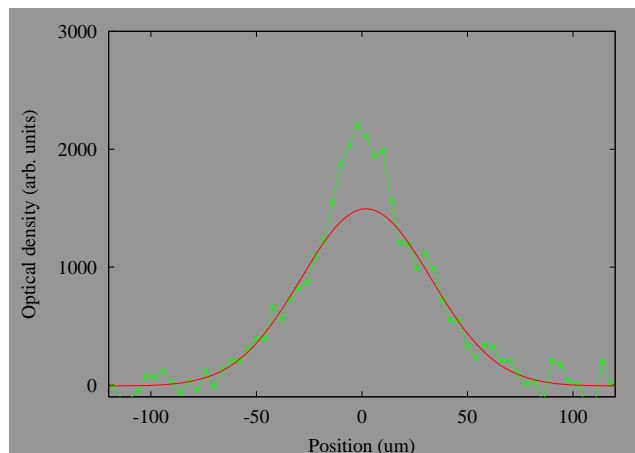


BEC

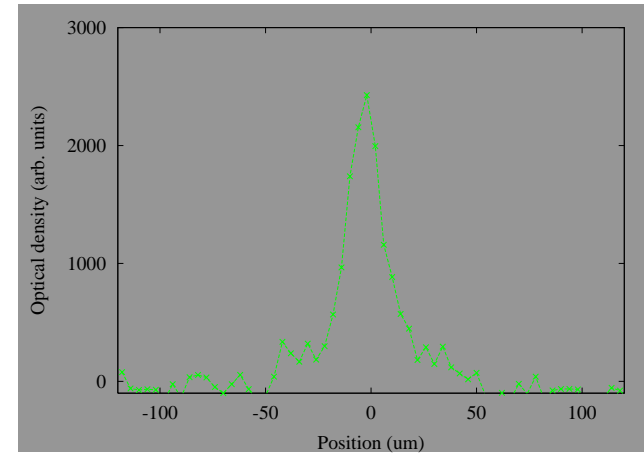
$T=350$ nK



$T=200$ nK



$N \sim 1 \times 10^4$



By mass scaling law we can know the scattering lengths of all the isotopes

Formation of Quantum Degenerate Gas

^{174}Yb (31.8%)

Boson, $I=0$

^{170}Yb (3.05%)

Boson, $I=0$

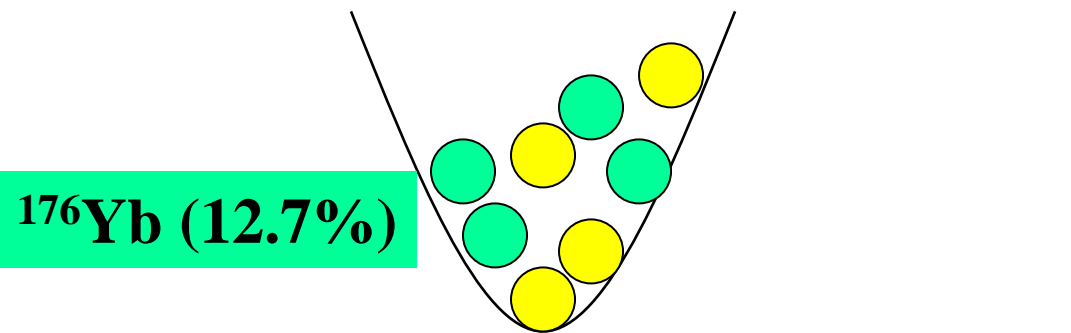
^{176}Yb (12.7%)



Boson, $I=0$

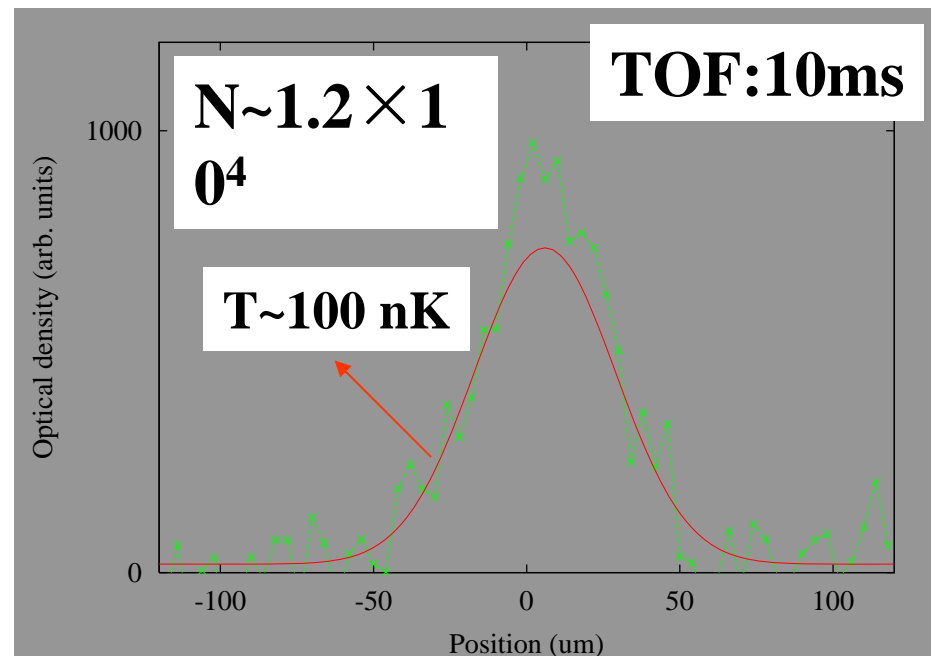
^{173}Yb (16.2%)

Fermion, $I=5/2$

^{176}Yb BEC: sympathetic cooling with boson ^{174}Yb

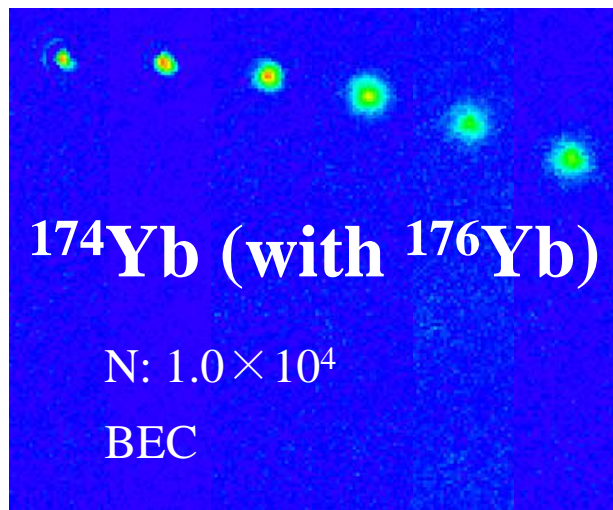


 ^{176}Yb : small collision rate
 ^{174}Yb : large collision rate

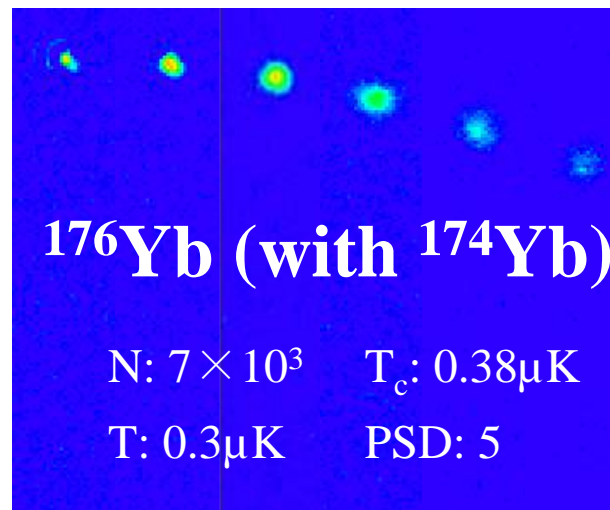


TOF (ms)

0 1 2 3 4 5



0 1 2 3 4 5

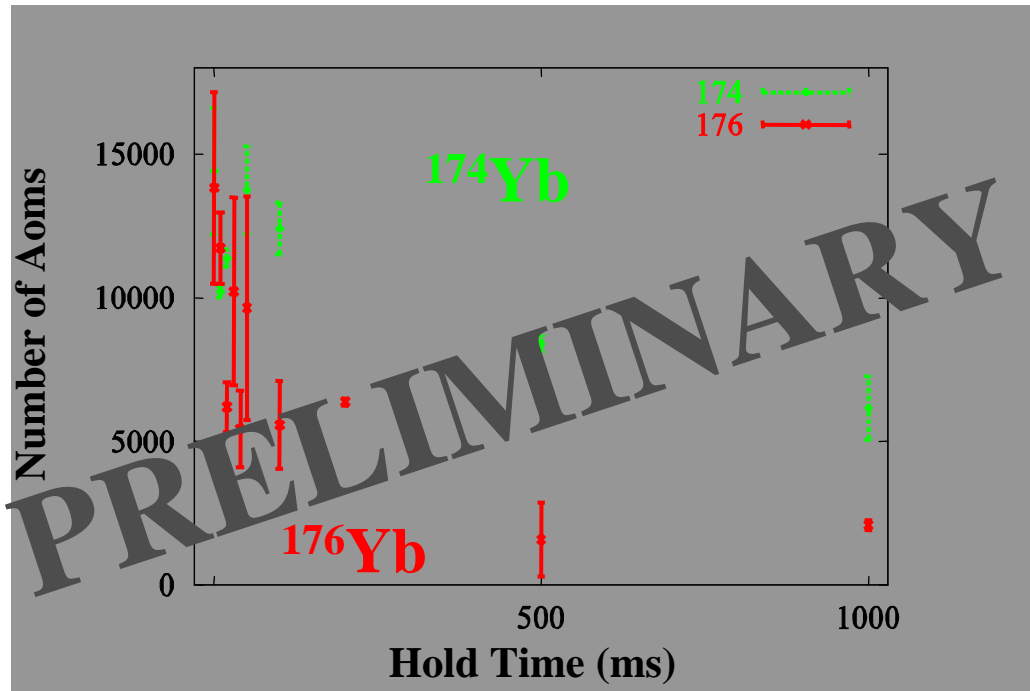


^{176}Yb BEC: sympathetic cooling with boson ^{174}Yb

“Further evaporative cooling did not increase the condensate fraction”

Possibility

$$a_{176} < 0 \quad : \text{attractive interaction} \quad N_C \approx 0.6 \times \frac{a_{osc}}{|a_{176}|}$$
$$\sim 600 \quad \text{if } a_{176} = -1 \text{ nm}$$



Formation of Quantum Degenerate Gas

^{174}Yb (31.8%)

Boson, $I=0$

^{170}Yb (3.05%)

Boson, $I=0$

^{176}Yb (12.7%)

Boson, $I=0$

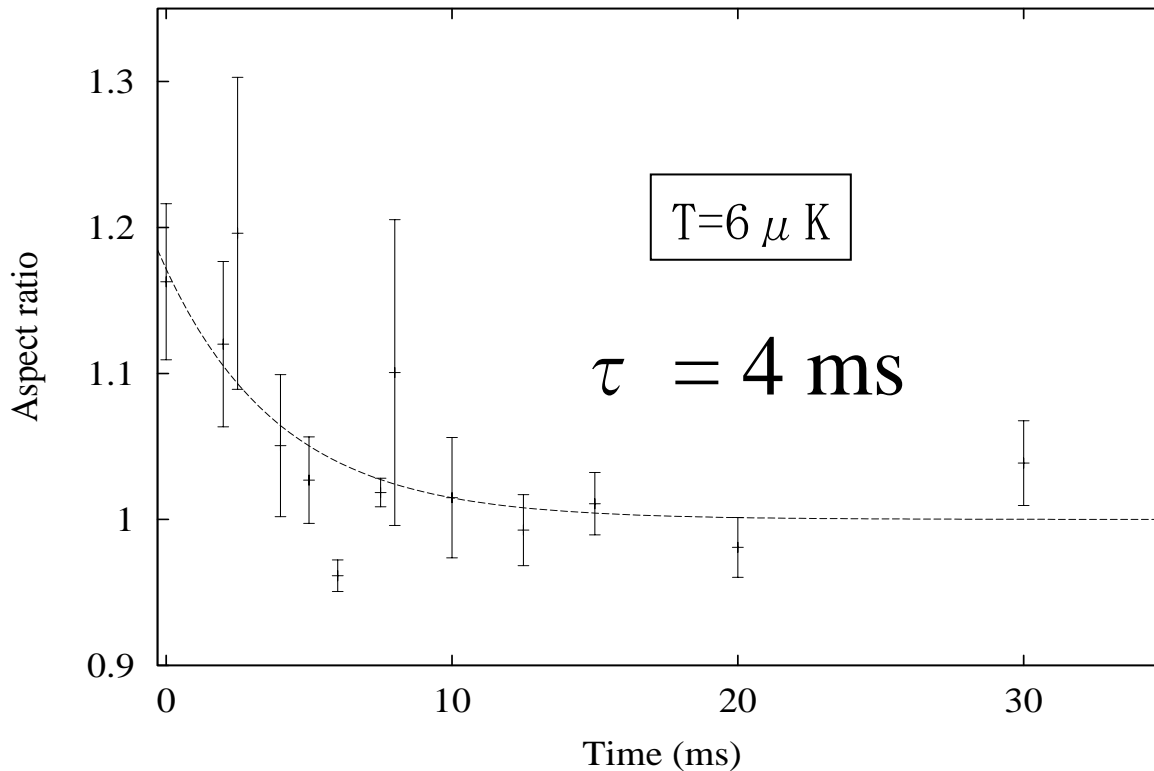
^{173}Yb (16.2%)

Fermion, $I=5/2$

^{173}Yb Fermi Degeneracy

^{173}Yb (16.2%, $I=5/2$)

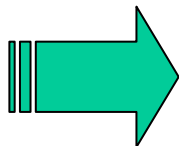
$m_F = -5/2, -3/2, -1/2, +1/2, +3/2, +5/2$



Anisotropy in Temperature
by Parametric Heating



Observe Re-thermalization

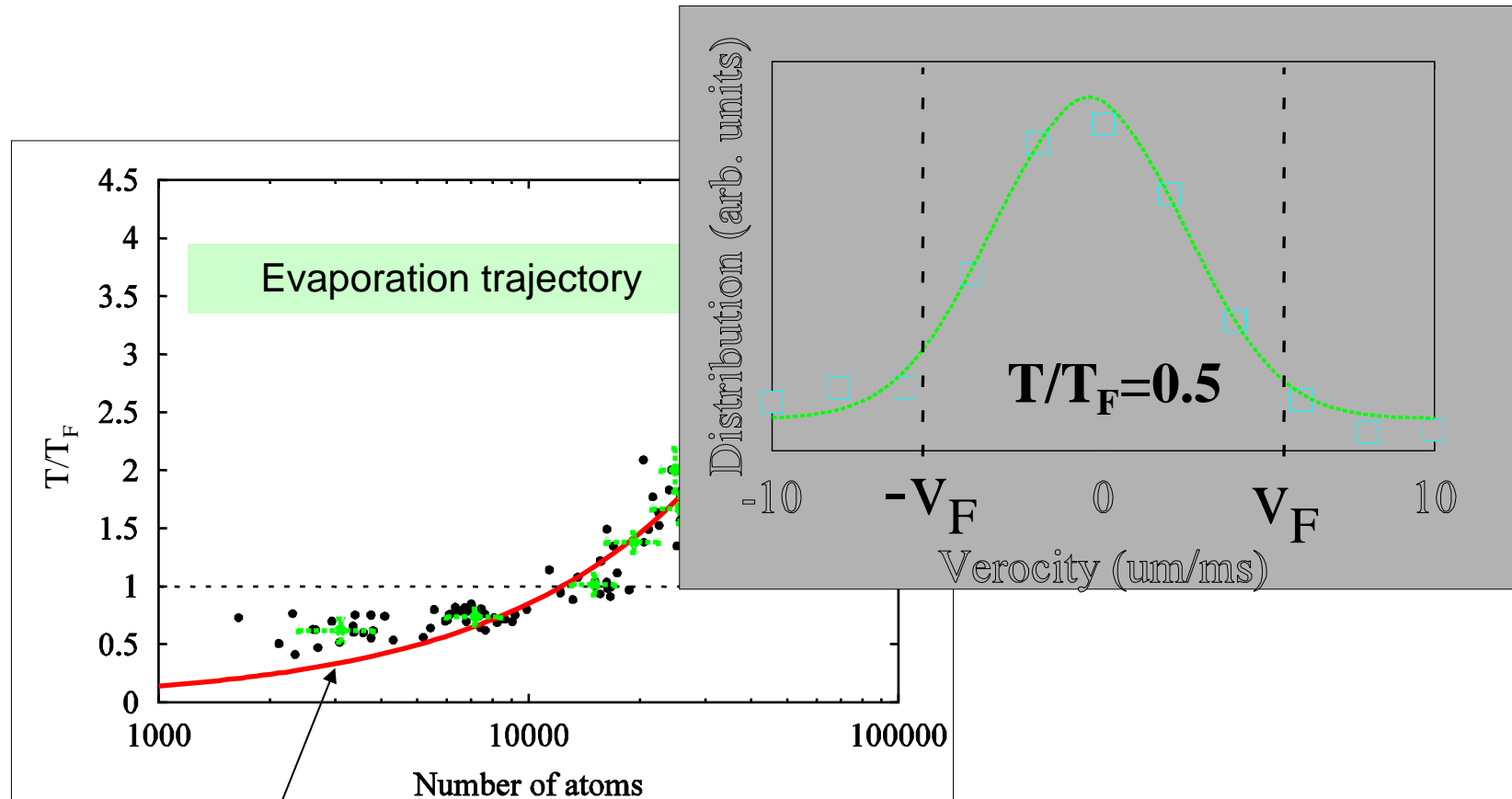


$$|a| \approx 6 \text{ nm} \pm 2 \text{ nm}$$

^{173}Yb Fermi Degeneracy

^{173}Yb (16.2%, $I=5/2$)

$m_F = -5/2, -3/2, -1/2, +1/2, +3/2, +5/2$



onset of Fermi degeneracy

$T/T_F \sim 0.5$

Atomic BEC and Fermi Degeneracy

1995	^{87}Rb ^{23}Na ^7Li
1998	^1H
1999	^{40}K
2000	^{85}Rb
2001	^{41}K $^4\text{He}^*$ ^6Li
2003	^{133}Cs ^{174}Yb
2005	^{52}Cr
2006	^{170}Yb ^{176}Yb ^{173}Yb $^3\text{He}^*$

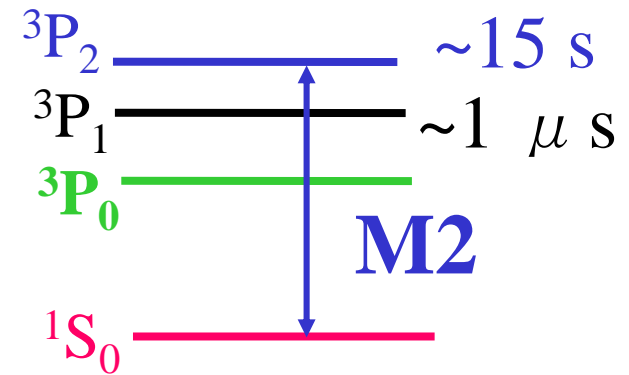
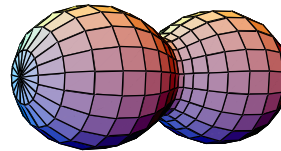
Future Possibilities

Ultra-Narrow Optical Transition

1S_0 - 3P_2 (507 nm: linewidth ~ 10 mHz)



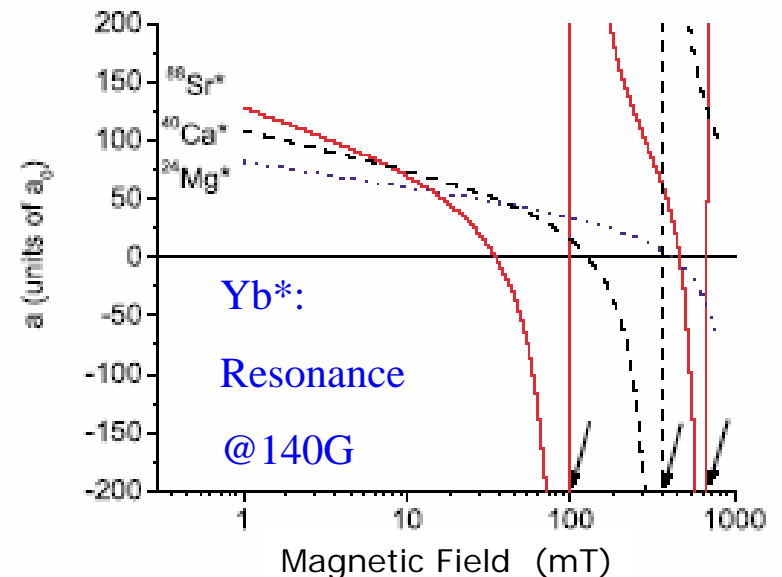
Creating BEC in the 3P_2 state



— dipolar BEC: $\mu(^3P_2)=3\mu_B$

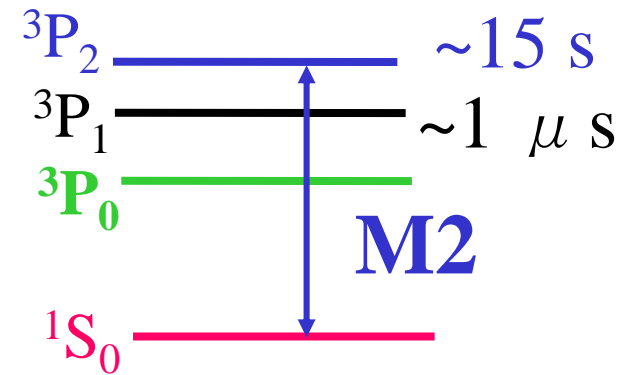
— Tuning the scattering length

[A. Derevianko *et al.*, PRL **90**, 063002(2003)]



Ultra-Narrow Optical Transition

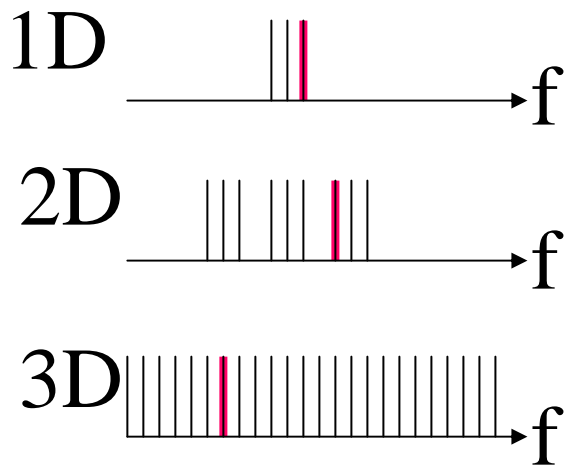
1S_0 - 3P_2 (507 nm: linewidth ~ 10 mHz)



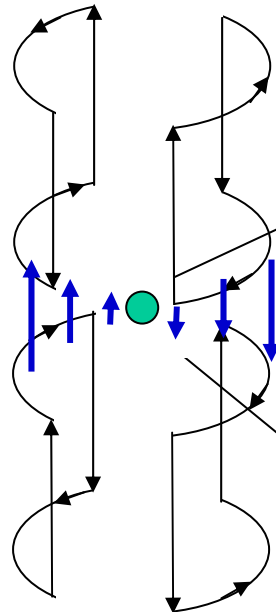
Optical Magnetic Resonance Imaging

$$\partial B_z / \partial x = 10 \text{ G/cm}, \delta\nu = 1 \text{ kHz}$$

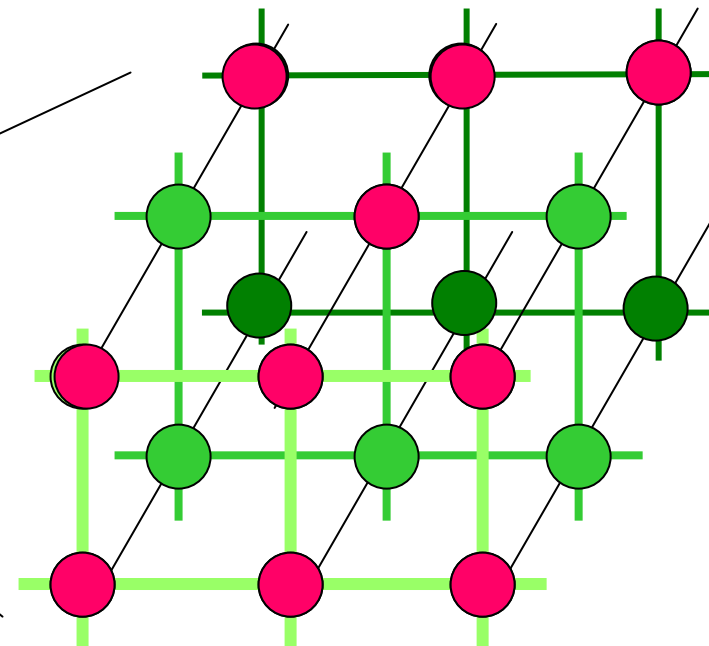
$$\delta x = 250 \text{ nm}$$



$B_0 // z$



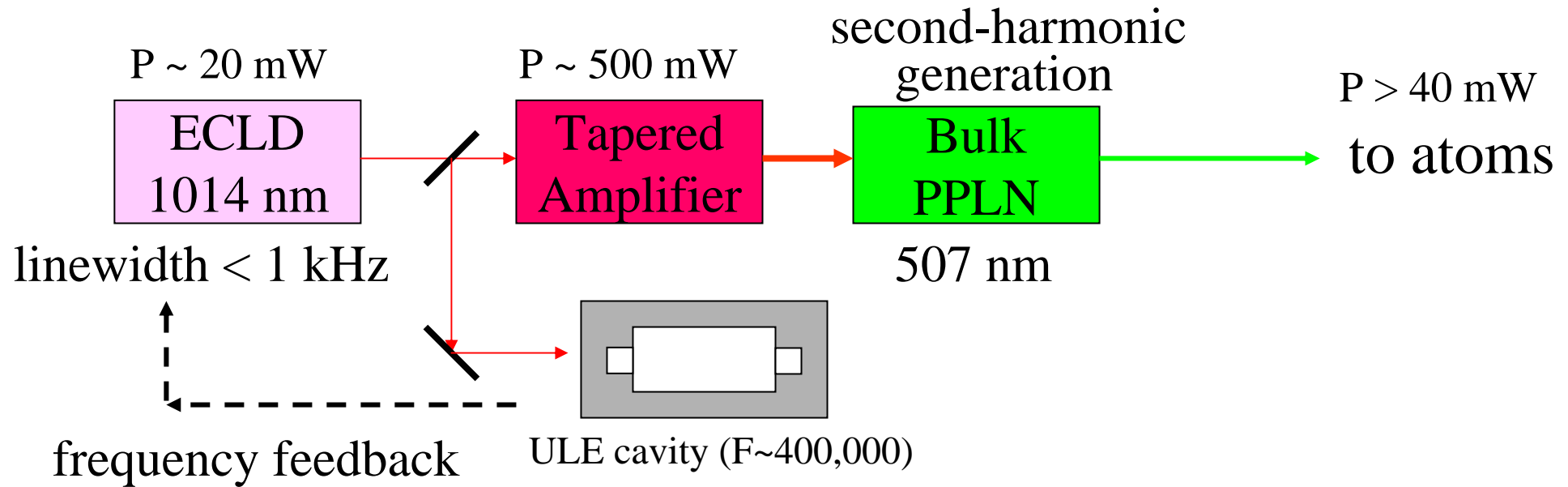
“Optical Lattice”



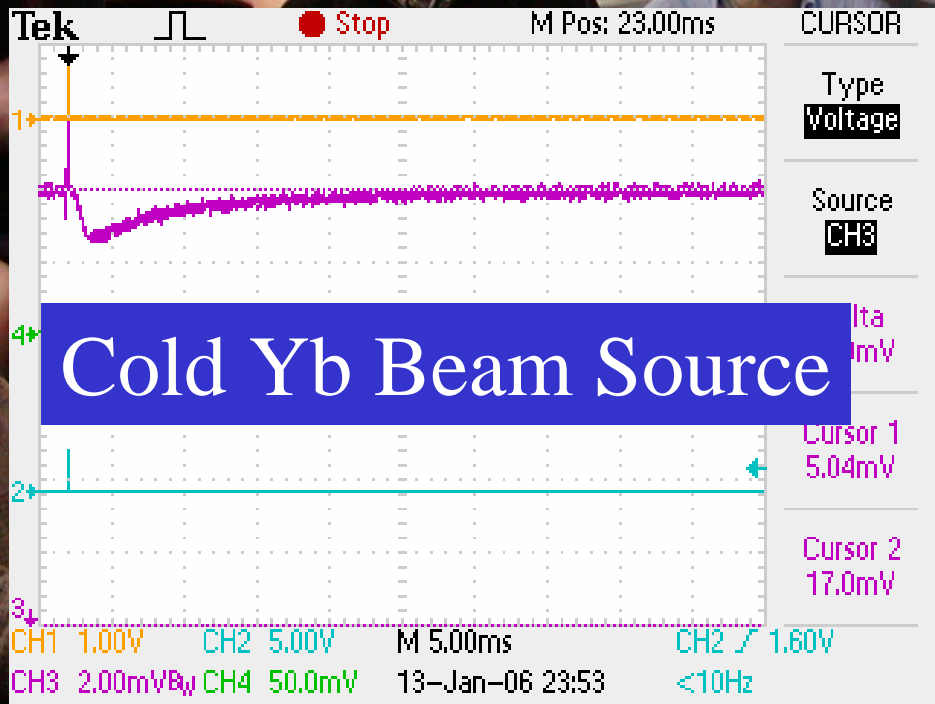
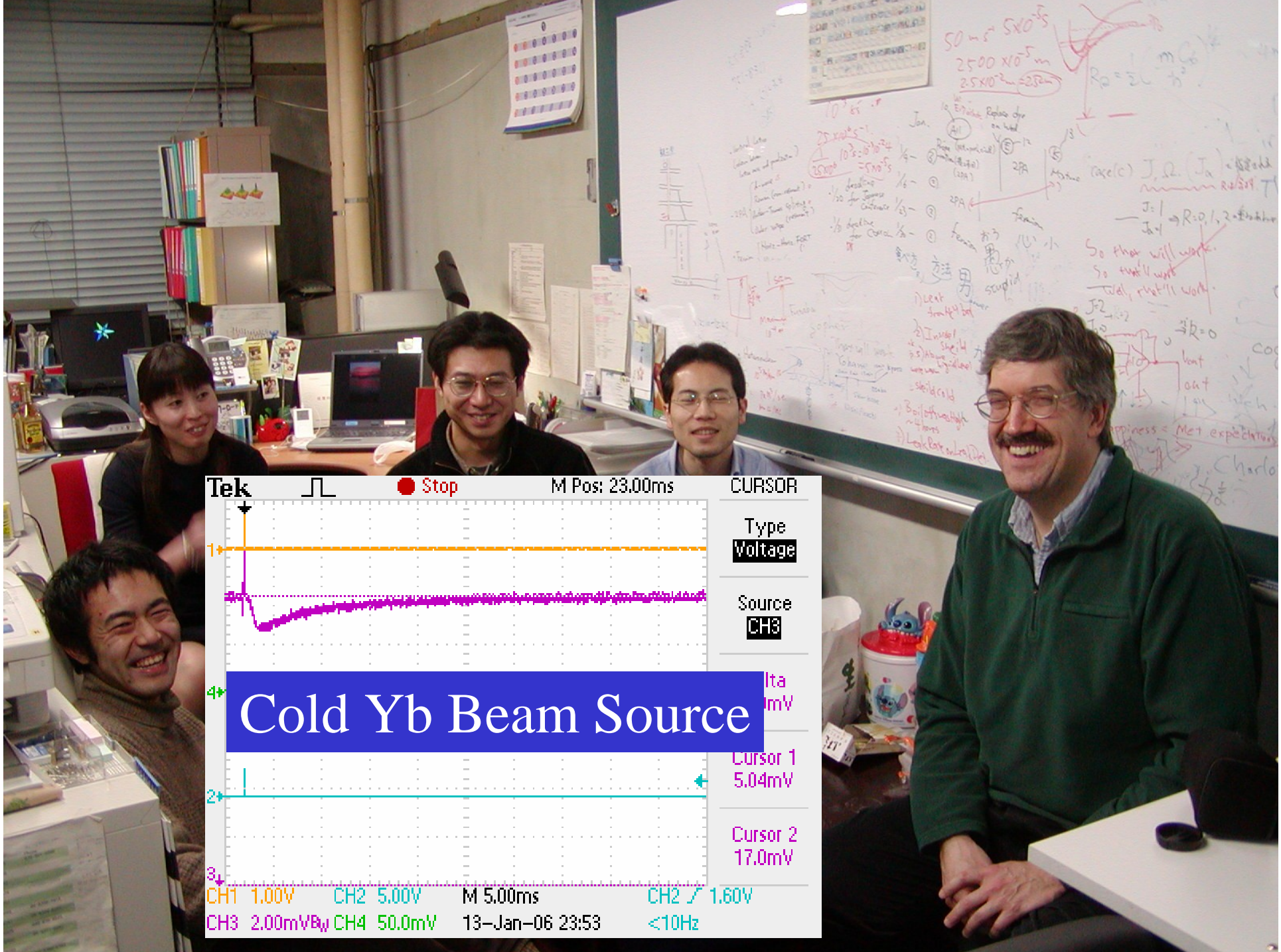
Use of Ultra-narrow Optical Transition

development of stable light source:

1S_0 - 3P_2 (507 nm: linewidth $\ll 1$ kHz)



under construction



Thank you very much for attention.

