

Variance Measurement of m_p/m_e Using Cold Molecules

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Measurement of **vibrational** transition frequency of magnetically trapped XH molecules (X: even isotope of alkali earth atoms)
within the uncertainty of 10^{-15}

Observation of the **variance in m_p/m_e** with high sensitivity using also two atomic transitions

Utility of measurement of the variance in m_p/m_e

Proof of Grand Unification Theory (GUT)

(possibility to detect the variance in fundamental constants)

$$d \ln (m_p/m_e) / dt = R_c d \ln (\alpha) / dt$$

$$R_c = 36? \quad \alpha: \text{fine structure constant}$$

(actual value of R_c depends on the detail of GUT)

Molecular Transition Frequency $\leftrightarrow m_p/m_e$
(atomic transition freq. is independent to m_p/m_e)

$$d \ln (\nu) / dt = \mathbf{S} \times d \ln (m_p/m_e) / dt$$

S = -0.5 pure **vibrational** transition frequency (IR)

S = -1 pure **rotational** transition frequency (MW)

S = -4.2 NH_3 **inversion** transition (MW)

Freq. uncertainty is lowest with vibrational transition

Detection of variance in m_p/m_e

Astronomical Results

E. Reinhold et al., Phys. Rev. Lett. 96, 151101 (2006).

$$\Delta (m_p/m_e) / (m_p/m_e) = (2 \pm 0.6) \times 10^{-5}$$

$$(z = 2.5 - 3)$$

10 billions light years

V. V. Flambaum, Phys. Rev. Lett 98, 240801 (2007).

$$\Delta (m_p/m_e) / (m_p/m_e) = (0.6 \pm 1.9) \times 10^{-6}$$

$$(z = 0.68)$$

Measurement in a Laboratory

- **Using a Thermal Beam**

SF₆ vibrational

A. Shelkovernikov et. al., Phys. Rev. Lett 100, 150801 (2008).

$$d \ln (m_p / m_e) / dt = (3.8 \pm 5.8) \times 10^{-14} / \text{yr}$$

- **Using Cold Molecules (in procedure)**

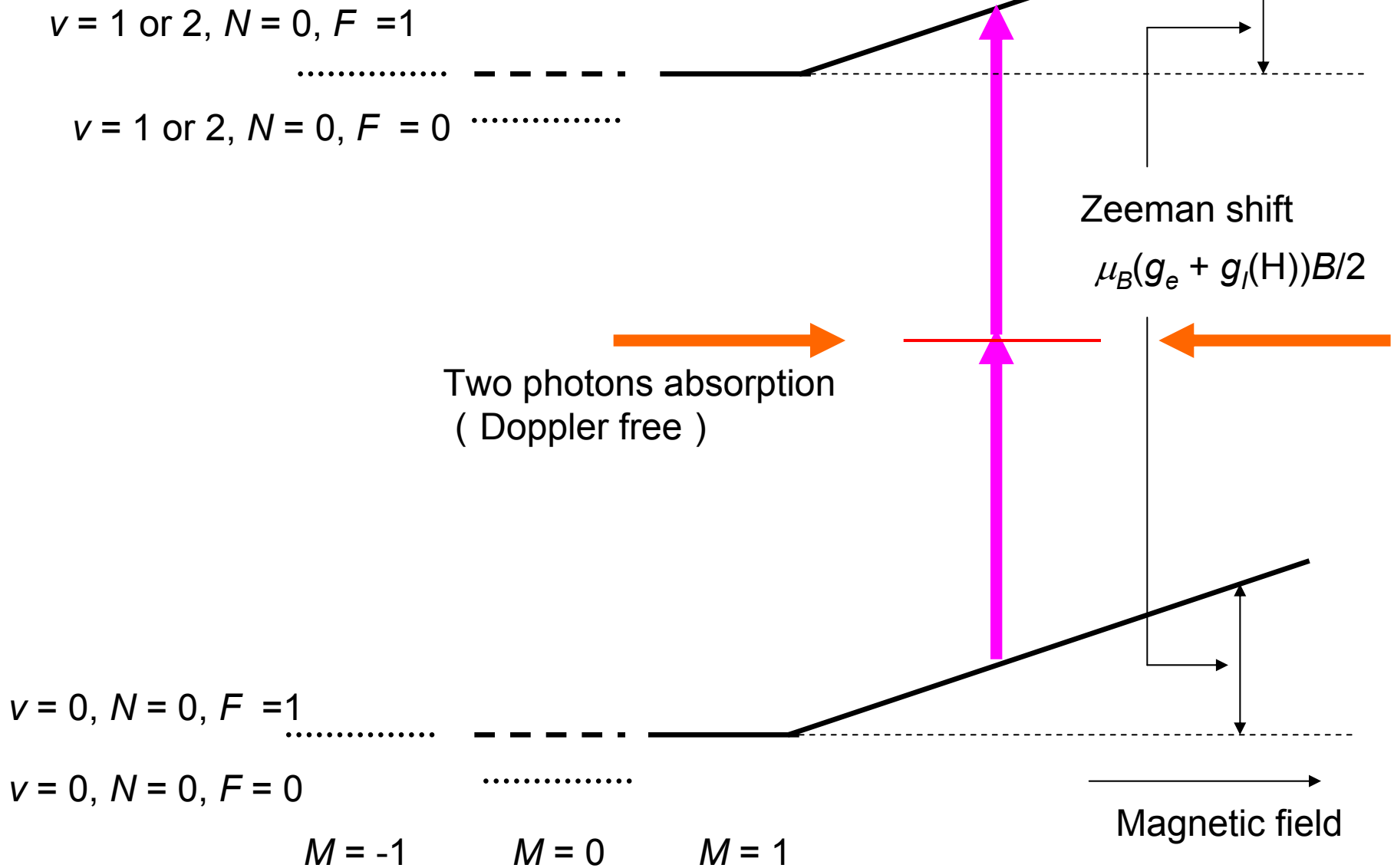
NH₃ fountain (Amsterdam)

H₂⁺ HD⁺ (Duesseldorf U.)

Pure vibrational transition of trapped molecules

- **Long interaction time with probe laser reduces the homogeneous linewidth.**
 - **Stark shift is significant for electrically trapped molecules, because the dipole moment etc. depend on the vibrational state.**
 - **We can measure the transition frequency of magnetically trapped molecules, which is free from Zeeman shift.**
- (Zeeman coefficient is mostly independent to vibrational state)**

XH ($^2\Sigma$ state) X: even isotope of Alkali-earth atom
 (X nuclear spin is zero)



Transition Frequency and Natural Linewidth

- ^{24}MgH

$\nu = 0 \rightarrow 1$ 4.29×10^{13} Hz (two photon 14.2 μm)

$\nu = 0 \rightarrow 2$ 8.39×10^{13} Hz (two photon 7.2 μm)

Natural linewidth 0.82 Hz

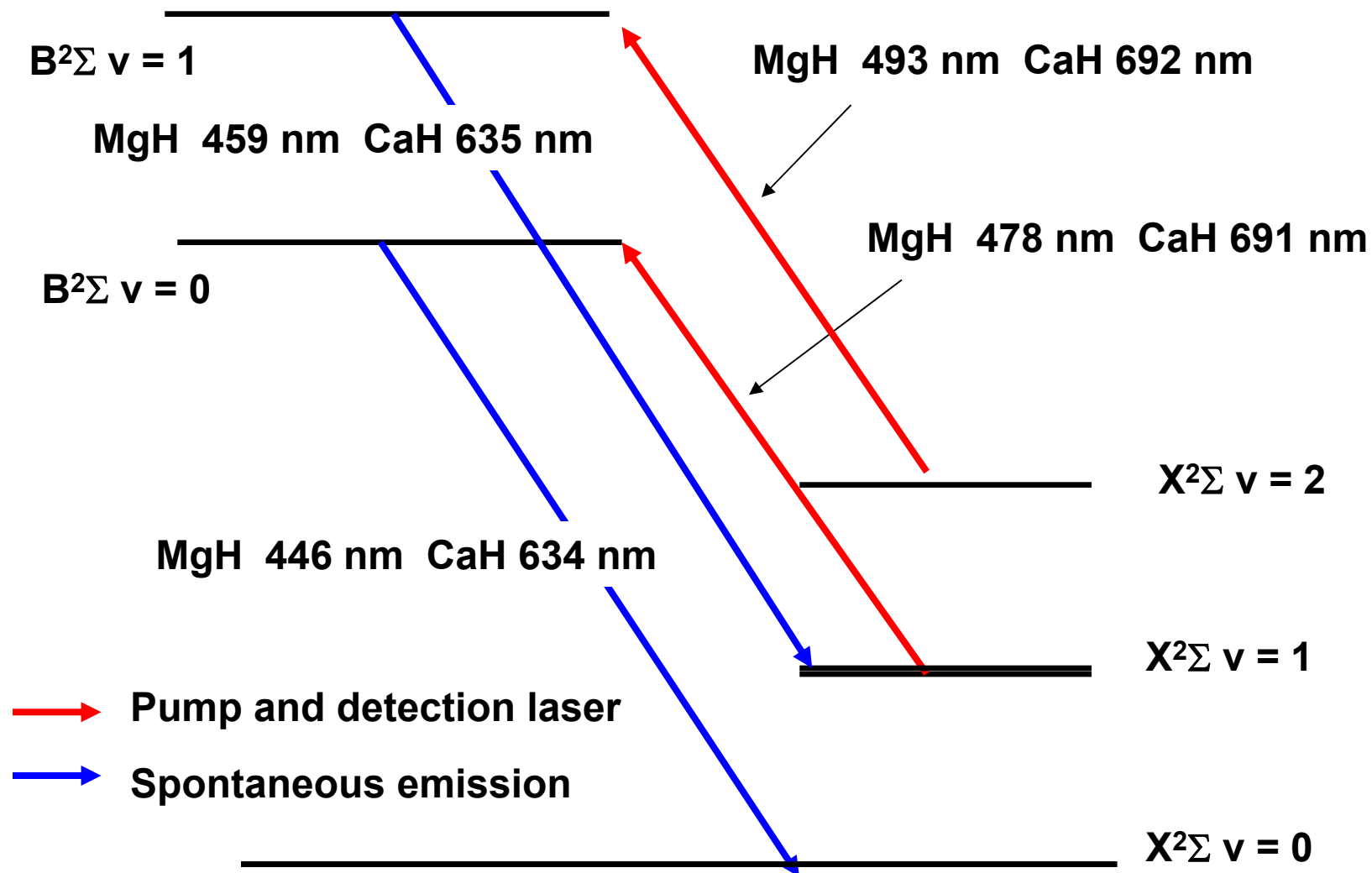
- ^{40}CaH

$\nu = 0 \rightarrow 1$ 3.78×10^{13} Hz (two photon 15.8 μm)

$\nu = 0 \rightarrow 2$ 7.44×10^{13} Hz (two photon 7.8 μm)

Natural linewidth 2.23 Hz

Detection and Pumping of molecules in the vibrational excited state



Measurement Procedure

Laser ablation on $XH_2 \rightarrow$ production of XH

Loading to magnetic trap using buffer gas (1 K)

Pumping vibrational excited molecules down to the ground state

Reduction of magnetic field gradient
reduce density + adiabatic cooling (< 10 mK) + evaporative cooling

Irradiation of probe laser (0.2 sec.)

Detection of molecules in vibrational excited state

Frequency Shift

Zeeman shift

Caused by Chemical shift for H nuclear spin

Temperature lower than 1 mK, $\Delta f/f < 10^{-15}$

Light shift

With saturation power I_s , 1.5×10^{-14} (5.0×10^{-15}) for ^{40}CaH (^{24}MgH)

$\Delta f/f < 10^{-15}$ taking $I/I_s = 1/10$

Collision Shift (Temperature is lower than 10 mK)

$\Delta f/f = -6 \times 10^{-26}$ (-4×10^{-27}) cm^3 for ^{40}CaH (^{24}MgH)

$\Delta f/f < 10^{-15}$ with density lower than $10^9/\text{cm}^3$

Pure vibrational transition of XH molecules

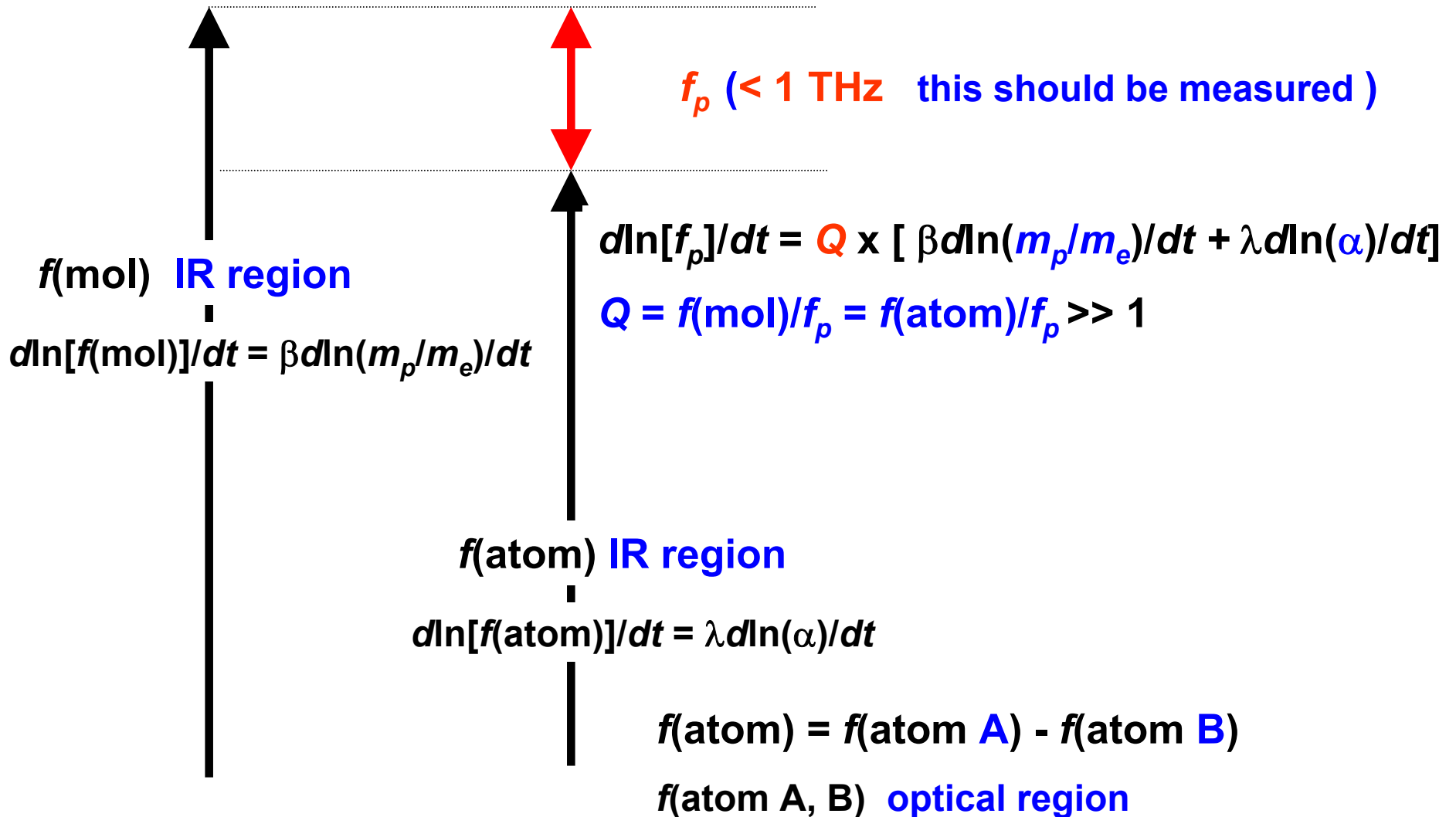
The uncertainty of

$(^2\Sigma, \nu = 0, N = 0, F = 1, M = 1) \rightarrow (^2\Sigma, \nu = 1 \text{ or } 2, N = 0, F = 1, M = 1)$

transitions of magnetically trapped XH molecules can be **lower than 10^{-15}**

Can we increase the sensitivity to (m_p/m_e) ?

Measurement in the THz Region



Combination 1

$$f(\text{Ca}^+) + f(\text{CaH})/2 - f(\text{Sr}) = 0.7 \text{ THz}$$

$$f(\text{Ca}^+): {}^2\text{S}_{1/2} \rightarrow {}^2\text{D}_{5/2} \quad 411.0 \text{ THz}$$

$$f(\text{Sr}): {}^1\text{S}_0 \rightarrow {}^3\text{P}_0 \quad 429.2 \text{ THz}$$

$$f(\text{CaH}): v = 0 \rightarrow 1 \quad 37.8 \text{ THz} \quad (\text{two photon})$$

$$d\ln[f_p]/dt = -13.5 d\ln(m_p/m_e)/dt + 52 d\ln(\alpha)/dt$$

Combination 2

$$f(\text{Al}^+) / 2 - f(\text{MgH})/2 - f(\text{Yb}) = 0.2 \text{ THz}$$

$$f(\text{Al}^+): {}^1\text{S}_0 \rightarrow {}^3\text{P}_0 \quad 1120.7 \text{ THz (frequency doubled)}$$

$$f(\text{Yb}): {}^1\text{S}_0 \rightarrow {}^3\text{P}_0 \quad 518.2 \text{ THz}$$

$$f(\text{MgH}): v = 0 \rightarrow 2 \quad 83.9 \text{ THz (two photon)}$$

$$d\ln[f_p]/dt = 63.5 d\ln(m_p/m_e)/dt - 867 d\ln(\alpha)/dt$$

Conclusion

The uncertainty of

$(^2\Sigma, \nu = 0, N = 0, F = 1, M = 1) \rightarrow (^2\Sigma, \nu = 1 \text{ or } 2, N = 0, F = 1, M = 1)$
transitions of magnetically trapped XH (X: ^{24}Mg , ^{40}Ca etc.)
molecules can be **lower than 10^{-15}** , because the Zeeman shift is
very small.

These transitions are useful for measurement of the **variance of electron-proton mass ratio**.

The sensitivity on the **variance of electron-proton mass ratio** is increased using the combination with two atomic transition frequencies in the optical region.