イッテルビウム同位体シフトデータの一般化線形性同時解析による新物理探索

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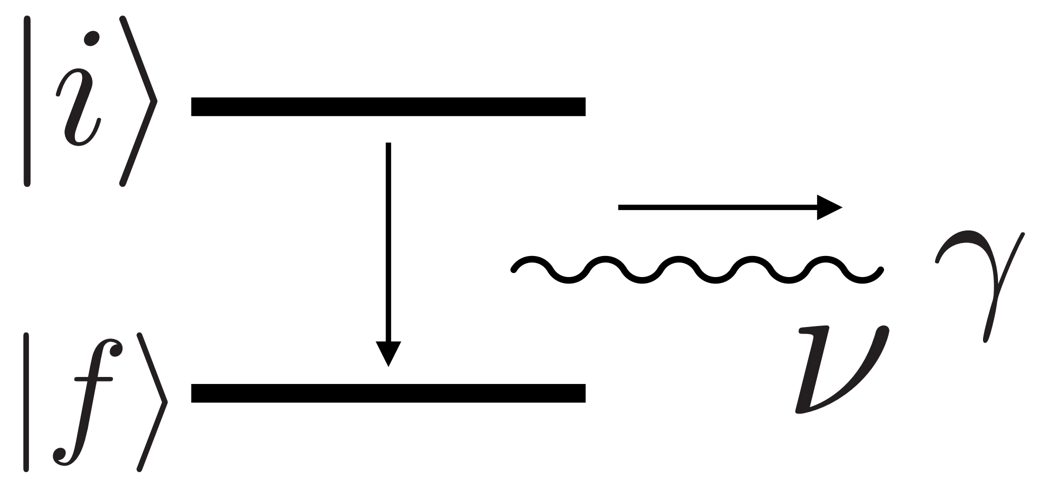
Isotope shift (IS) and King linearity



Level-splitting difference between isotopes

$$\mathrm{IS} = \nu_{A'A} := \nu_{A'} - \nu_{A}$$

IS of two transitions: $t = 1, 2$

$$\nu^{(t)}_{A'A} = K_t \mu_{A'A} + F_t \langle r^2 \rangle_{A'A}$$

mass shift (MS) field shift (FS)

$$\mu_{A'A} := 1/m_{A'} - 1/m_{A}$$

$$\langle r^2 \rangle_{A'A} := \langle r^2 \rangle_{A'} - \langle r^2 \rangle_{A}$$

Modified IS: $\tilde{\nu}^{(t)}_{A'A} := \nu^{(t)}_{A'A} / \mu_{A'A} = K_t + F_t \langle r^2 \rangle_{A'A} / \mu_{A'A}$

electronic factors nuclear factor

King linearity: eliminating the nuclear factor King, 1963

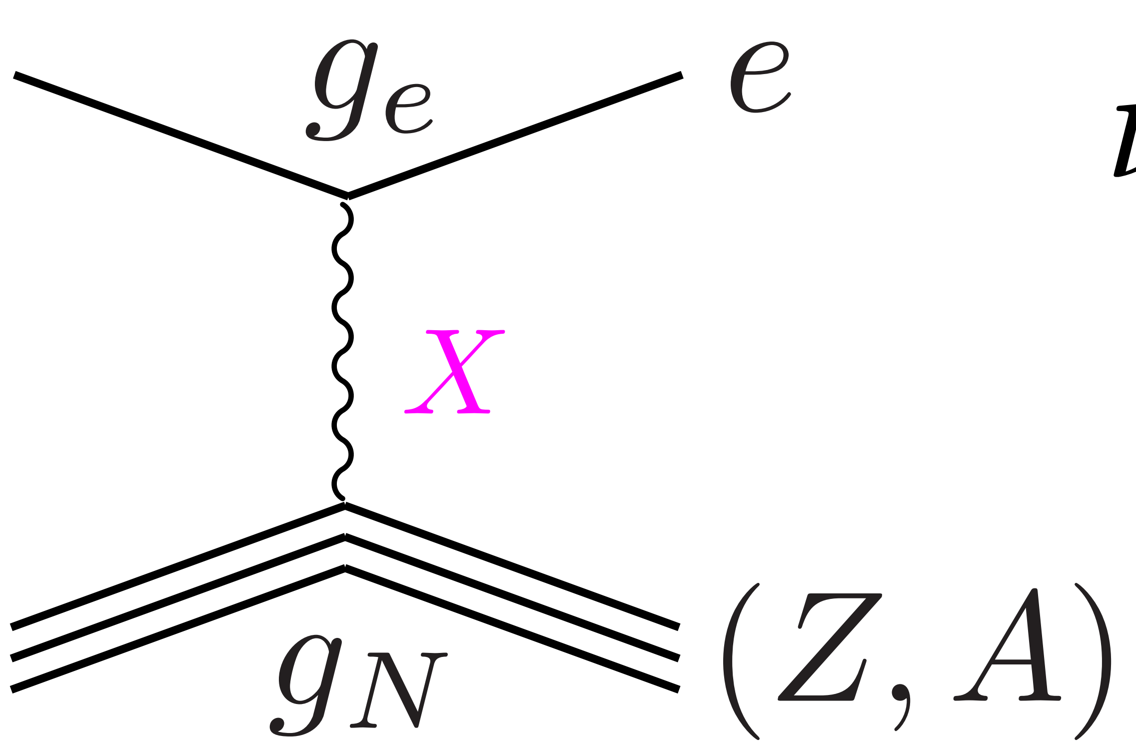
$$\tilde{\nu}^{(2)}_{A'A} = K_{21} + F_{21} \tilde{\nu}^{(1)}_{A'A}$$

$$K_{21} := K_2 - F_{21} K_1 \,, \; F_{21} := F_2 / F_1$$

→ $(\tilde{\nu}^{(1)}_{A'A}, \tilde{\nu}^{(2)}_{A'A})$ on a straight line, King plot

Nonlinearity

IS by new neutron-electron interaction   Delaunay et al. arXiv:1601.05087v2



$$\nu^{(t)}_{A'A} = K_t \mu_{A'A} + F_t \langle r^2 \rangle_{A'A} + X_t (A' - A)$$

MS   FS   particle shift (PS)

Nonlinearity due to subleading FS

$$\mathrm{FS} = F_t \langle r^2 \rangle_{A'A} + F'_t [\langle r^2 \rangle_{A'A}]^2 + G_t \langle r^4 \rangle_{A'A} + \cdots$$

quadratic FS (FS_{22})   higher moment (FS_4)

$$[\langle r^2 \rangle_{A'A}]^2 := (\langle r^2 \rangle_{A'A_0})^2 - (\langle r^2 \rangle_{AA_0})^2$$

Generalized linearity

K. Mikami, MT, Y. Yamamoto EPJC77:896 (2017)

$$\nu^{(t)}_{A'A} = K_t \mu_{A'A} + F_t \langle r^2 \rangle_{A'A} + F'_t [\langle r^2 \rangle_{A'A}]^2 + X_t (A' - A)$$

3 transitions: t=1, 2, 3 FS$_{22}$ PS

$$\begin{pmatrix} \nu^{(1)}_{A'A} - X_1(A'-A) \\ \nu^{(2)}_{A'A} - X_2(A'-A) \\ \nu^{(3)}_{A'A} - X_3(A'-A) \end{pmatrix} = \begin{pmatrix} K_1 & F_1 & F'_1 \\ K_2 & F_2 & F'_2 \\ K_3 & F_3 & F'_3 \end{pmatrix} \begin{pmatrix} \mu_{A'A} \\ \langle r^2 \rangle_{A'A} \\ [\langle r^2 \rangle_{A'A}]^2 \end{pmatrix} =: M \begin{pmatrix} \mu_{A'A} \\ \langle r^2 \rangle_{A'A} \\ [\langle r^2 \rangle_{A'A}]^2 \end{pmatrix}$$

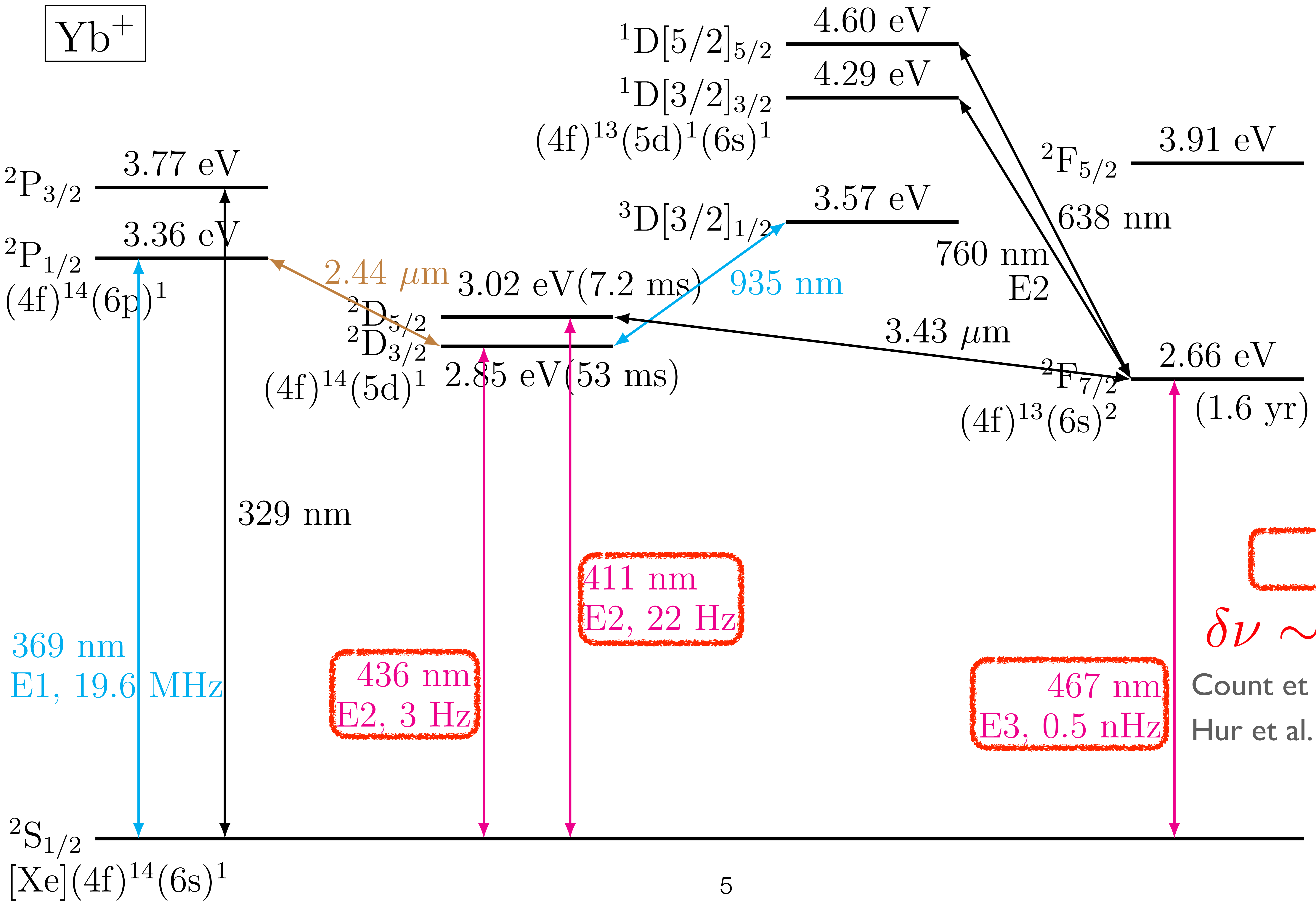
$$\rightarrow (M^{-1})_{11}\nu^{(1)}_{A'A} + (M^{-1})_{12}\nu^{(2)}_{A'A} + (M^{-1})_{13}\nu^{(3)}_{A'A}$$
$$- \{(M^{-1})_{11}X_1 + (M^{-1})_{12}X_2 + (M^{-1})_{13}X_3\}(A'-A) = \mu_{A'A}$$

$(\nu^{(1)}_{A'A}, \nu^{(2)}_{A'A}, \nu^{(3)}_{A'A})/\mu_{A'A}$ on a plane if $X_t = 0$

n transitions and n+1 IS pairs → NP search with n-2 NL's removed

Data of Yb transitions

LS coupling $^{2s+1}L_J$

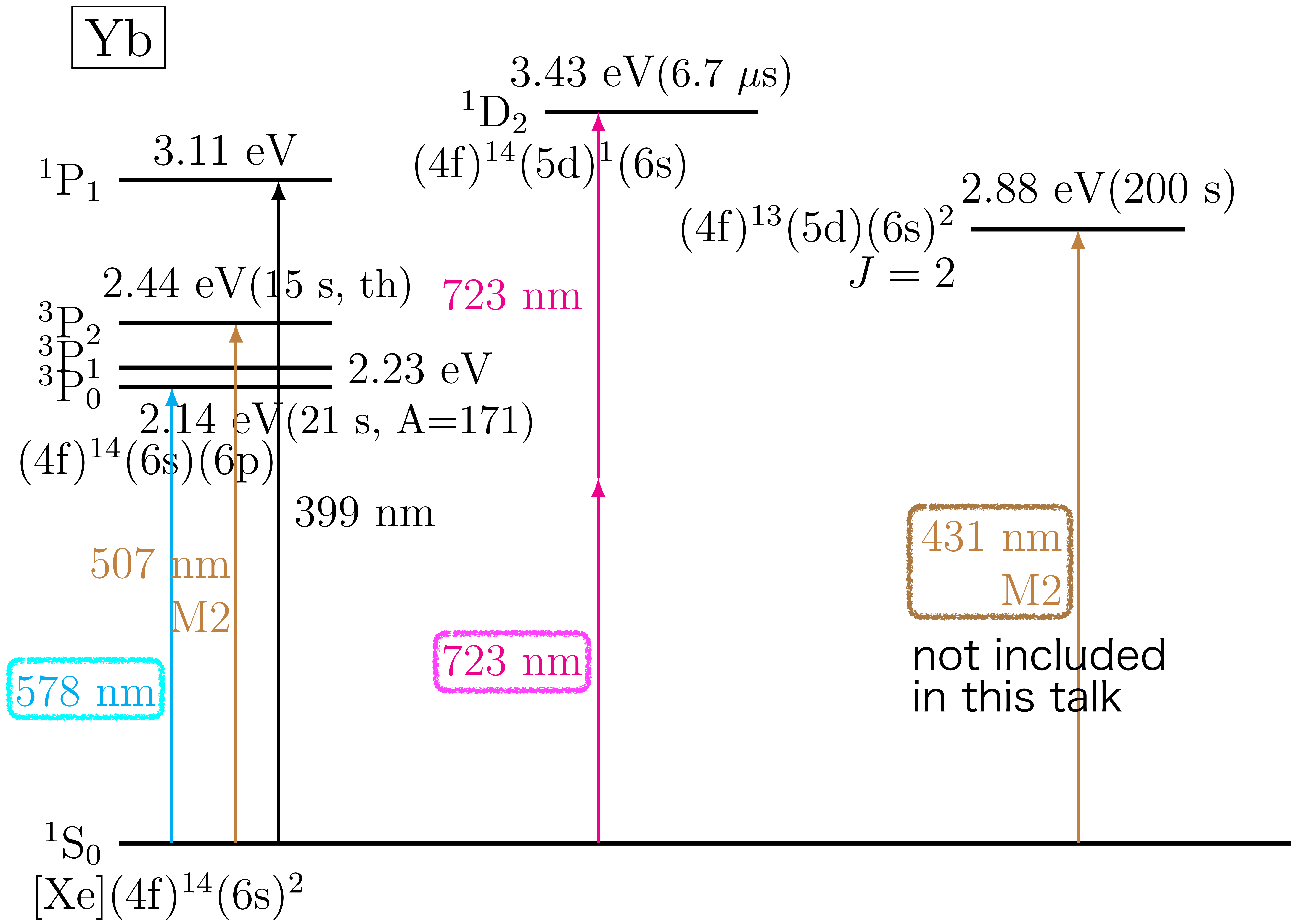


MIT

$\delta\nu \sim 300 - 500$ Hz

Count et al. PRL 125, 123002 (2020)

Hur et al. PRL 128, 163201 (2022)



LS coupling

$^{2s+1}L_J$

Kyoto

$\delta\nu \sim$ a few Hz

K. Ono, MT et al. PRX 12, 021033 (2022)

Mainz

Figueroa et al. PRL 128, 073001 (2022)

$\delta\nu \sim O(100)$ Hz

Kyoto

T. Ishiyama et al. PRL 130, 153402 (2023)

石山さんの講演 20pA2-4

NMIJ,AIST

A. Kawasaki et al. arXiv:2402.13541

Simultaneous analysis of plural linearities

Y.Yamamoto, MT et al. in preparation

Yb: 4 independent IS pairs

3D linearity is nontrivial, while 5 transitions available.

→ Combined fit of 3 independent 3D relations

$$\nu_3 = k_3\mu + f_{31}\nu_1 + f_{32}\nu_2\,,\ \ \nu_4 = k_4\mu + f_{41}\nu_1 + f_{42}\nu_2\,,\ \ \nu_5 = k_5\mu + f_{51}\nu_1 + f_{52}\nu_2$$

($A'A$ omitted)

$\delta\chi^2/\mathrm{dof} = 35.1/3$

Assigning this nonlinearity to PS,

→ $\delta\chi^2/\mathrm{dof} = 9.98/1$

PS alone cannot explain the observed 3D nonlinearity.

Consistency with SM sources

$$\mathrm{FS} = F_t \langle r^2 \rangle_{A'A} + F'_t [\langle r^2 \rangle_{A'A}]^2 + G_t \langle r^4 \rangle_{A'A} + \cdots$$

FS_{22} FS_4

Using theoretically calculated electronic factors, we subtract FS_{22} and/or FS_4.

	D5	D3	F7	P0	D2	
FS_{22} (a)	81.908	83.247	-201.12	54.277	75.322	(AMBiT) Hur et al. PRL 128, 163201 (2022)
FS_4 (g)	14.934	15.159	-39.422	8.951		(GRASP2018)
FS_4 (r)	13.08				10.42	(RPA) Figueroa et al. PRL 128, 073001 (2022)

(MHz/fm^4)

Abbreviation: (Yb^+) $\mathrm{D5} := {}^2\mathrm{S}_{1/2} - {}^2\mathrm{D}_{5/2}$, $\mathrm{D3} := {}^2\mathrm{S}_{1/2} - {}^2\mathrm{D}_{3/2}$, $\mathrm{F7} := {}^2\mathrm{S}_{1/2} - {}^2\mathrm{F}_{7/2}$

(Yb) $\mathrm{P0} := {}^1\mathrm{S}_0 - {}^3\mathrm{P}_0$, $\mathrm{D2} := {}^1\mathrm{S}_0 - {}^1\mathrm{D}_2$

Hypothesis: FS_4 and one unknown

No FS_4 in $\nu'_i := \nu_i - p_{i/i_0}\nu_{i_0}\,,\ p_{i/i_0} := G_i/G_{i_0}$ ratio of FS_4 electronic factor

→ Two independent 3D linear relations (i_0 = D5)

$$\nu'_i = k_i\mu + d_i\nu'_{\mathrm{P0}} + e_i\nu'_{\mathrm{D2}}\,,\ i = \mathrm{D3,\ F7}$$

$$\delta\chi^2/\mathrm{dof} = 13.3/2 \text{ without theoretical uncertainty}$$

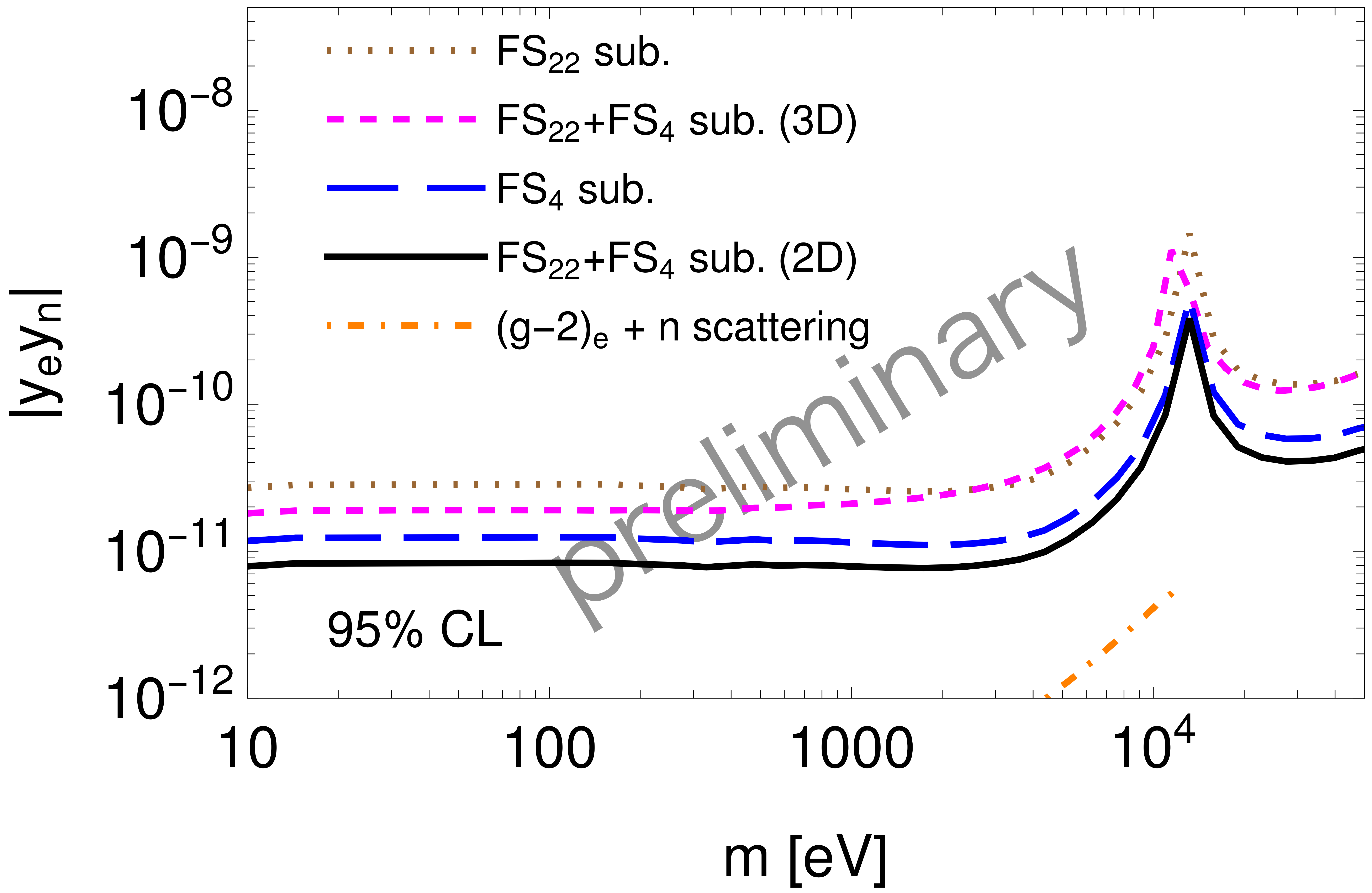
$$\delta\chi^2/\mathrm{dof} = 1.8/2 \text{ with 6\% theoretical uncertainty for } p\text{'s}$$

→ Limit on new physics (not to make the fit worse)

$$\nu'_i := \nu_i - p_{i/i_0}\nu_{i_0} - \frac{y_e y_n}{4\pi}X_i(m)(A' - A)$$

$$|y_e y_n| < 1.2\times 10^{-11}\,,\ m = 10\ \mathrm{eV}\ (95\%\ \mathrm{CL})$$

Summary of limit on new physics



Minoru TANAKA

まとめと展望

- Isotope shift and King linearity $\tilde{\nu}^{(2)}_{A'A} = K_{21} + F_{21}\tilde{\nu}^{(1)}_{A'A}$

  IS=MS+FS, linear relation of mIS of two transitions
- Nonlinearities : New physics and/or SM higher order
- Generalized linearity

  SM nonlinearity removed, improved sensitivity to new physics

  Two or more SM higher order contributions revealed

  One SM higher order + PS, excluded by our combined analysis
- New precise Yb IS data

  Yb^+ ion O(10) Hz, MPI-PTB Door et al. arXiv2403.07792

  improvement of MIT data and Yb masses

  Yb atom O(?) Hz, Kyoto 石山さんの講演 20pA2-4

  $^1S_0(6s)^2 - (4f)^{13}(5d)(6p)^2\ (J=2)\,,\ 431\ \mathrm{nm}$