A Hot Two-Photon E1-M1 Optical Clock

E.A. Alden and A.E. Leanhardt

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

80 $^1S_0$
Hg
Mercury
200.59
[Xe]$4f^{14}5d^{10}6s^2$
10.4375

Frequency Standards

$$\sigma_\nu = \frac{\Delta\nu}{\nu}\sqrt{\frac{T}{\tau N}}$$

$\Delta\nu$ transition linewidth
T experiment duty cycle
ν excitation laser frequency
τ total experiment time
N sample size

An allowed, two-photon E1-M1 transition from the $^1S_0$ ground state to the $^3P_0$ clock state creates a more portable optical frequency standard than the current generation of optical clocks. It can be implemented in thermal vapor cells. Improvements in frequency standards advance metrology for everyday applications such as GPS and for tests of fundamental physics.

E1-M1 Excitation Scheme

Probability of exciting an atom into $^3P_0$

Total number of addressed atoms

$$N_{^3P_0} = P_{^3P_0}(\Omega_{R2\gamma}, \bar{t}_B) \times N_{tot}(T, \omega_0)$$

$$\Omega_{R2\gamma} = \frac{2I}{\hbar^2 c^2 \epsilon_0}\frac{\langle ^3P_0||\mu||^3P_1\rangle_{M1}\langle ^3P_1||D||^1S_0\rangle_{E1}}{\Delta}$$

Atom	amu	n	E1/ea_0	M1/μ_B	$\Omega_{R2\gamma}[Hz]$
Ra	226.0	7	1.2 [7]	$\sqrt{1.9}$ [7]	1.4×10^3
Ba	137.3	6	0.45 [8]	$\sqrt{2}$	6×10^2
Yb	173.1	6	0.54 [9]	$\sqrt{2}$ [9]	5.1×10^2
Hg	200.6	6	0.44 [10]	$\sqrt{2}$	1.9×10^2
Sr	87.6	5	0.15 [11]	$\sqrt{2}$	1.8×10^2
Ca	40.1	4	0.036 [11]	$\sqrt{2}$	39
Mg	24.3	3	0.0057 [11]	$\sqrt{2}$ [10]	4.3
Be	9.1	2	0.00024 [10]	$\sqrt{2}$	0.19

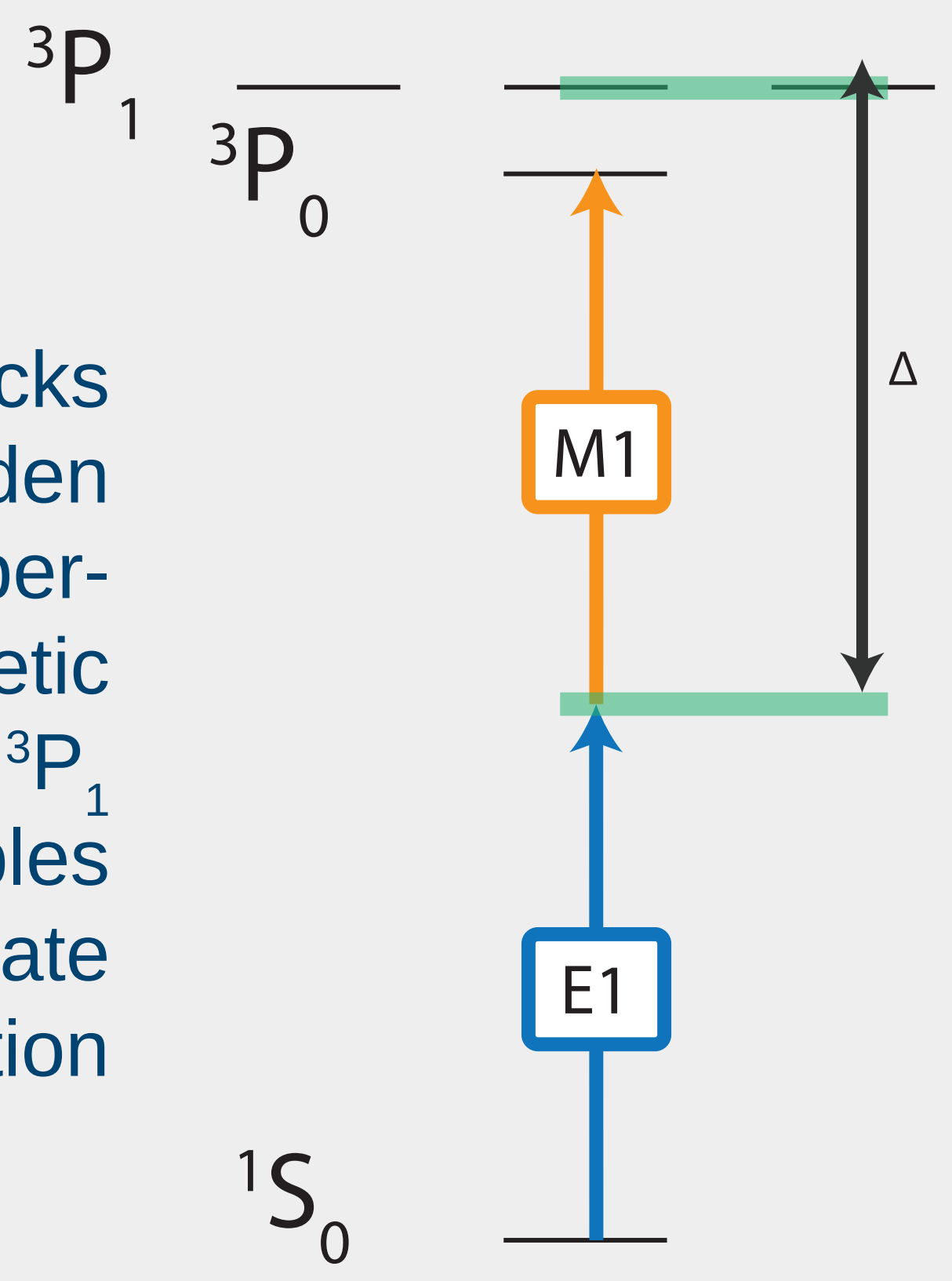
$$N_{tot}(T, \omega_0)$$

$$\frac{e^{\frac{-10^4}{T}}}{\sqrt{T}}\left\{\frac{1}{\omega_0} \atop \omega_0\right\}$$

Optimal Parameters

large T
small ω_0

Current optical-frequency atomic clocks based on the electric dipole E1 forbidden $^1S_0$ > $^3P_0$ transition require either hyperfine structure or an applied magnetic field to induce mixing of the $^3P_0$ and $^3P_1$ levels. A two-photon excitation couples the $^1S_0$ ground state to the $^3P_0$ clock state through an allowed E1 and M1 excitation sequence.



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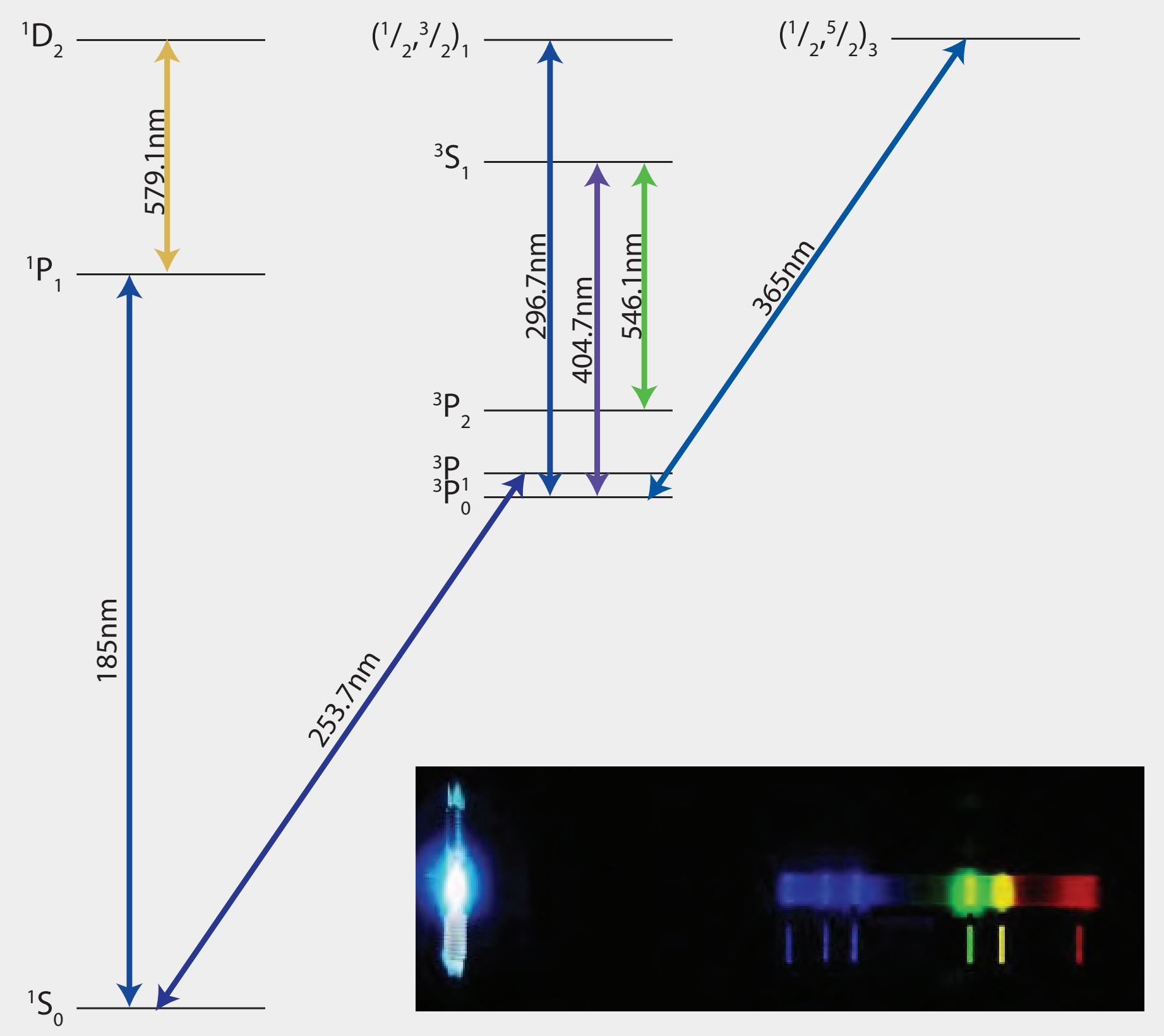
Stability and Rate Estimates

		σ_ν	
Atom	T	ω_0	σ_ν
Hg	520 K	8.6e-04	5.03e-16
Yb	800 K	1.0e-03	5.57e-14
Ra	800 K	1.0e-03	8.65e-14
Sr	800 K	1.0e-03	5.81e-13
Ba	800 K	1.0e-03	2.25e-12
Ca	800 K	1.0e-03	1.03e-11
Mg	800 K	1.0e-03	1.07e-11
Be	800 K	1.0e-03	5.73e-08

		N Clock Atoms	
Atom	T	ω_0	N_D
Hg	620 K	1.1e-04	6.24e+12
Yb	800 K	1.7e-04	3.42e+08
Ra	800 K	1.9e-04	1.63e+08
Sr	800 K	1.8e-04	8.12e+06
Ba	800 K	2.0e-04	4.40e+05
Ca	800 K	1.8e-04	5.31e+04
Mg	800 K	1.5e-04	4.75e+04
Be	800 K	1.5e-04	4.34e-03

Hg Electronic Structure

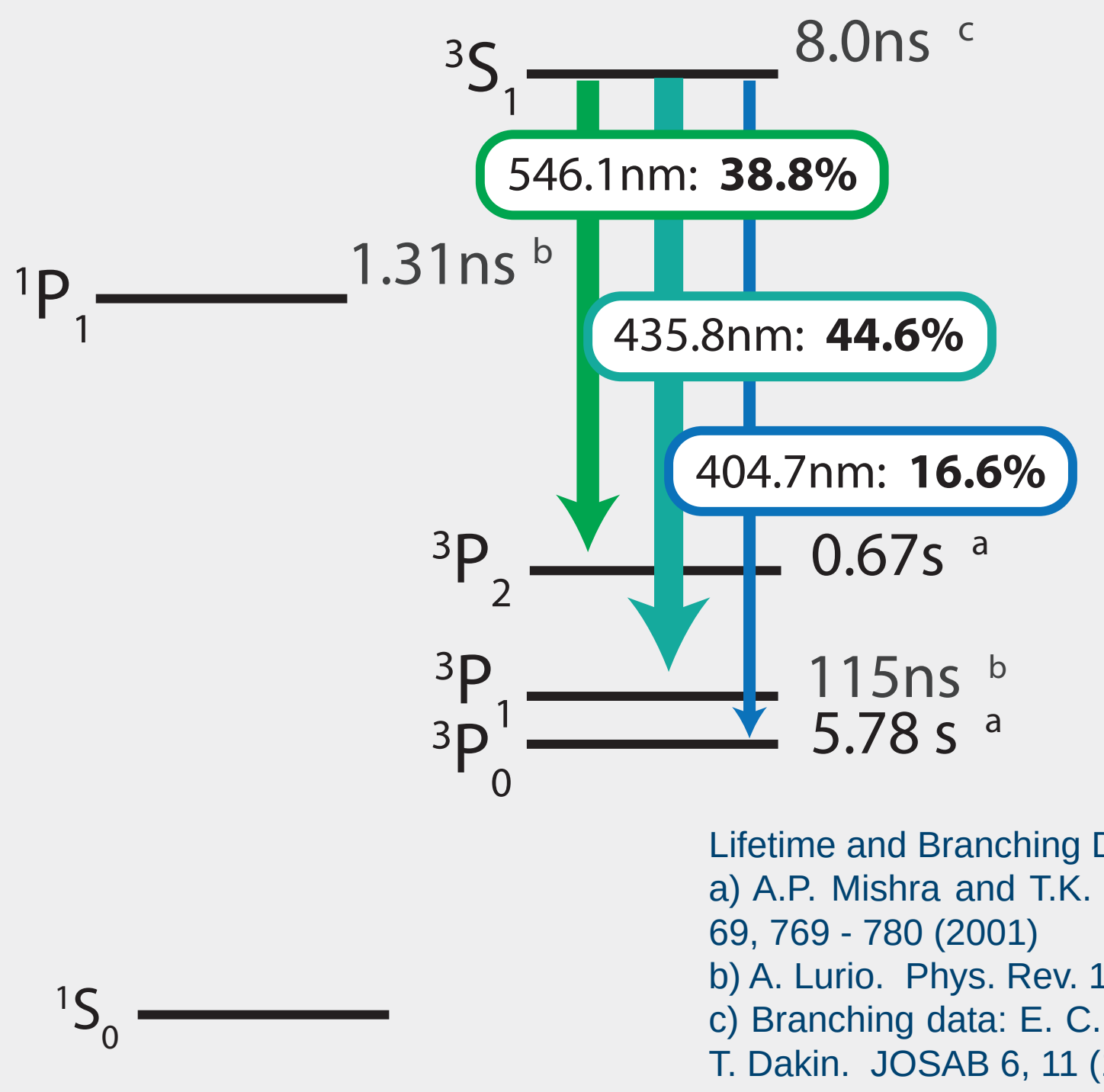


System	stability $\sigma_\nu\sqrt{\tau}$	Uncertainty σ_ν
$Hg_{2\gamma}$	10^{-16*}	*unk*
Al^+	3.7×10^{-16}	8.6×10^{-18}
Yb^+	3.2×10^{-16}	1.6×10^{-18}
Sr	2×10^{-15}	1×10^{-16}
Rb	7×10^{-16}	3.7×10^{-16}
Hg^+	9×10^{-15}	7×10^{-15}
$Hg_{1\gamma}$		5.7×10^{-15}
Yb	5.1×10^{-13}	1.4×10^{-15}
Cs	5.8×10^{-13}	10^{-15}
$Ag_{2\gamma}$	10^{-13*}	
Quartz	10^{-7}	
Chronometer	$10^{0.5}$	

Common Systems Instability and Realized Uncertainties
(* denotes theorized values not experimentally realized)

Experimental Setup

$^3P_0$ > $^3S_1$



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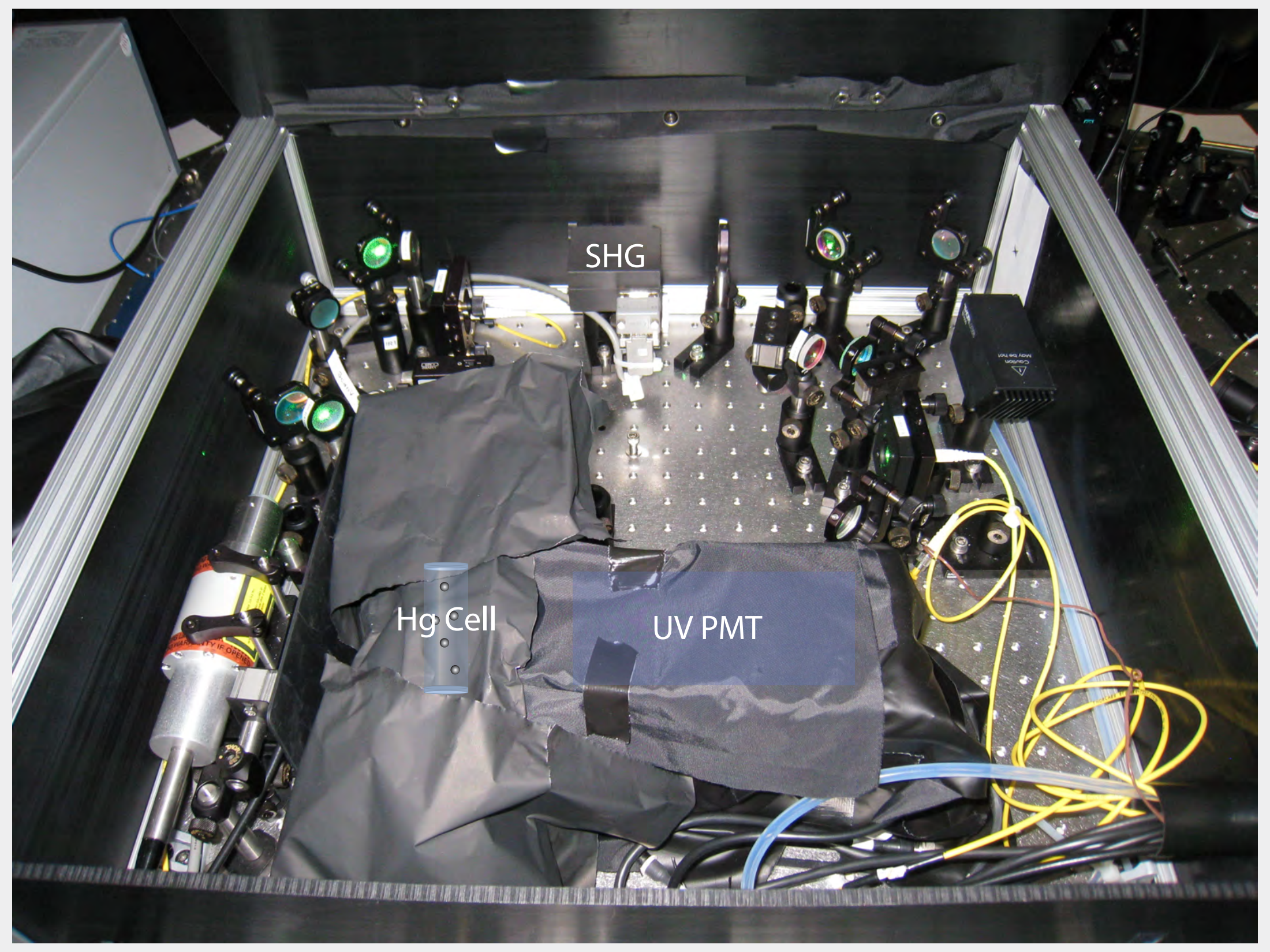

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