Title: Rotational analysis of a vibrational transition in the 199Hg2 molecule: a first step in an experimental realization of a spin-1/2 particle version of the EPR experiment Authors: Edward S. Fry and Xinmei Qu

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Abstract: An experimental realization of our spin-1/2 particle version of the Einstein-Podolsky-Rosen (EPR) experiment will be briefly reviewed. In the proposed experiment, two 199Hg atoms in the ground 1S0 electronic state, each with nuclear spin I=1/2, are generated in an entangled state with total nuclear spin zero. Such a state can be obtained by dissociation of a 199Hg2 molecule (dimer) using a spectroscopically selective stimulated Raman process. From symmetry considerations, the nuclear spin singlet state is guaranteed if the initial 199Hg2 molecule is in a rotational state with an even quantum number. Consequently, a thorough investigation and analysis of the rotational structure of the 199Hg2 molecule is required; results of this analysis will be presented.

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Einstein together with colleagues Podolsky and Rosen:

Quantum Mechanics is "incomplete"

Crux of the problem:

Classical mechanics gives deterministic predictions

Quantum mechanics gives statistical predictions or probabilities

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John Bell

Considered an EPR type experiment

Assumed:

1. Locality
2. "Completion" QM
3. Positive Probabilities

LOCALITY: Two spatially separated systems can affect each other only after a time delay greater than the time i takes light to travel from one system to the other.

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John Bell Proved:

1. The statistical predictions of any local theory that "completes" quantum mechanics in the sense of Einstein must satisfy an inequality.

2. The statistical predictions of quantum mechanics can violate that inequality.

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A definitive laboratory experiment is possible

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Initial experiments:

1972- Berkeley	violated Bell inequality and agreed with QM
1974- Harvard	satisfied Bell inequality and disagreed with QM
1976- TAMU	violated Bell inequality and agreed with QM
1982- Paris	violated Bell inequality and agreed with QM

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.

These initial experiments had loopholes; they required additional assumptions in order to make an experiment feasible.

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Some more recent experiments (also at least one loophole):

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Maryland then Rochester (1986-88) -

Two photon down conversion to test Bell inequality

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Austria (2003) -

Tested Bell inequality with space and spin components of a single neutron

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Note:

Results of Bell inequality experiments require any hidden variable theory to be non-local (in order to explain the data).

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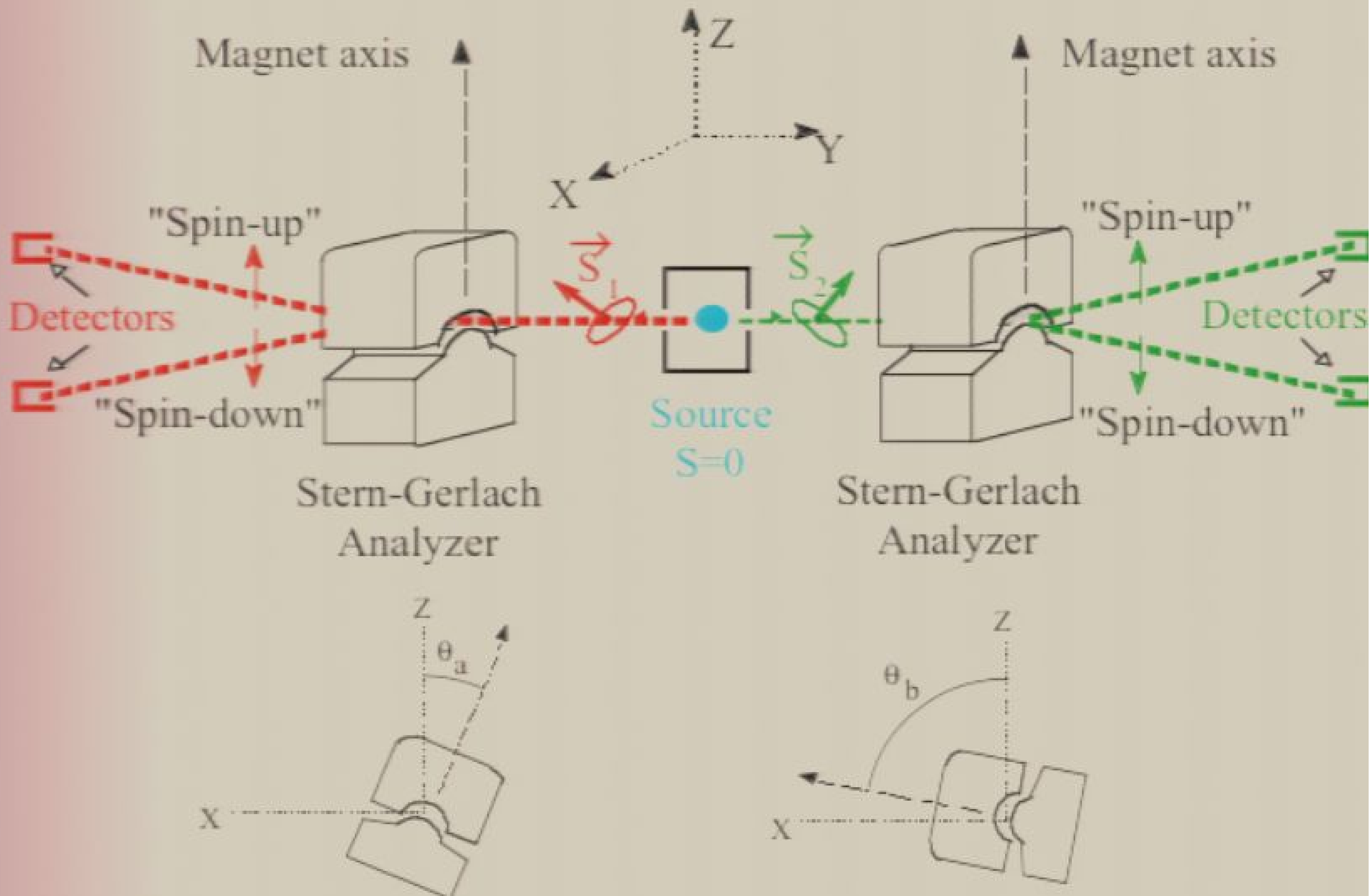
But, results of Bell inequality experiments do NOT require quantum mechanics to be non-local.

Bohm's version of EPR



$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left\{|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2\right\}$$

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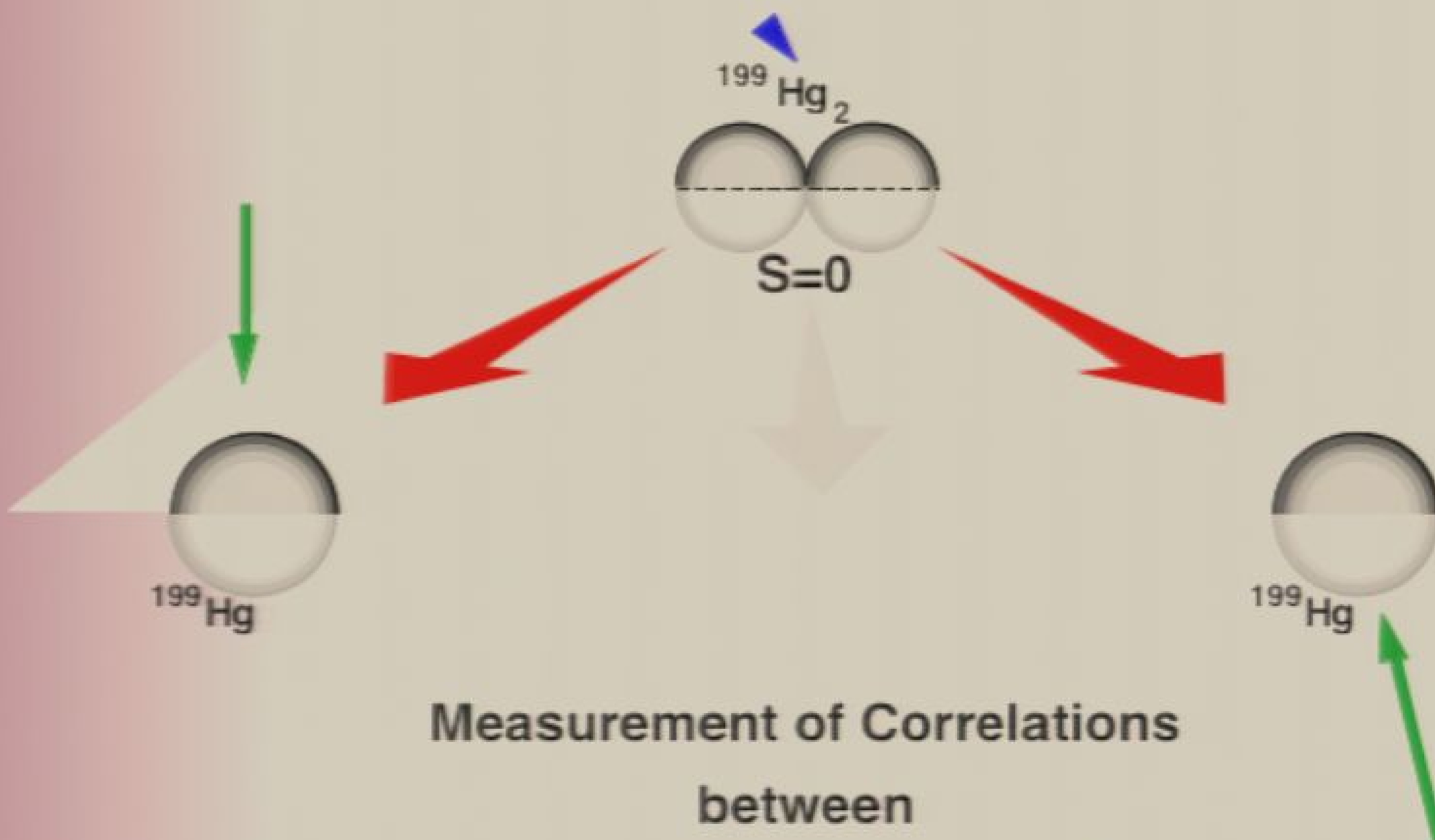
An experimental realization of Bohm's classic version of the Einstein-Podolsky-Rosen *gedankenexperiment*



Measurement of Correlations

between

Components of Nuclear Spin

T e x a s A & M

P h y s i c s

Features

When testing a fundamental concept, it is vital to do the study over as wide a range of the parameters as possible.

Our experiment with ^{199}Hg dimers dramatically extends the parameter range over which Bell inequalities are tested:

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Our experiment with ^{199}Hg dimers dramatically extends the parameter range over which Bell inequalities are tested:

1) Efficient detectors:

Detection efficiency of ≈100% closes the efficiency loophole.

2) Einstein locality:

Locality can be strictly enforced.

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3) Spin one-half fermions rather than bosons:

A ^{199}Hg atom is a fermion.

The first test of a Bell inequality with entangled fermions. The particles obey completely different quantum statistics than in all previous bell inequality tests.

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3) Spin one-half fermions rather than bosons:

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4) Massive particles vs. massless photons:

Nonrelativistic massive particles obey the non-relativistic Schrödinger equation; photons are very different.

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4) Massive particles vs. massless photons:

Nonrelativistic massive particles obey the non-relativistic Schrödinger equation; photons are very different.

A test of a Bell inequality with massive particles is in a regime very different from tests with photons.

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5) Inside the light cone rather than on it:

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Massive particles must have a velocity less than c and trace out a world line inside the light cone.

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Since photons travel with the velocity of light in any reference frame, they cannot be strictly localized.

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6) Entangled state exists for milliseconds:

In photon experiments, the entangled state typically exists a few nanoseconds before annihilation at the detectors.

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7) Spatially separated and independent storage of the two components of the entangled state:

Frozen neon matrices offer the capability to store the two components of the entangled state in separate and movable locations for relatively long periods of time.

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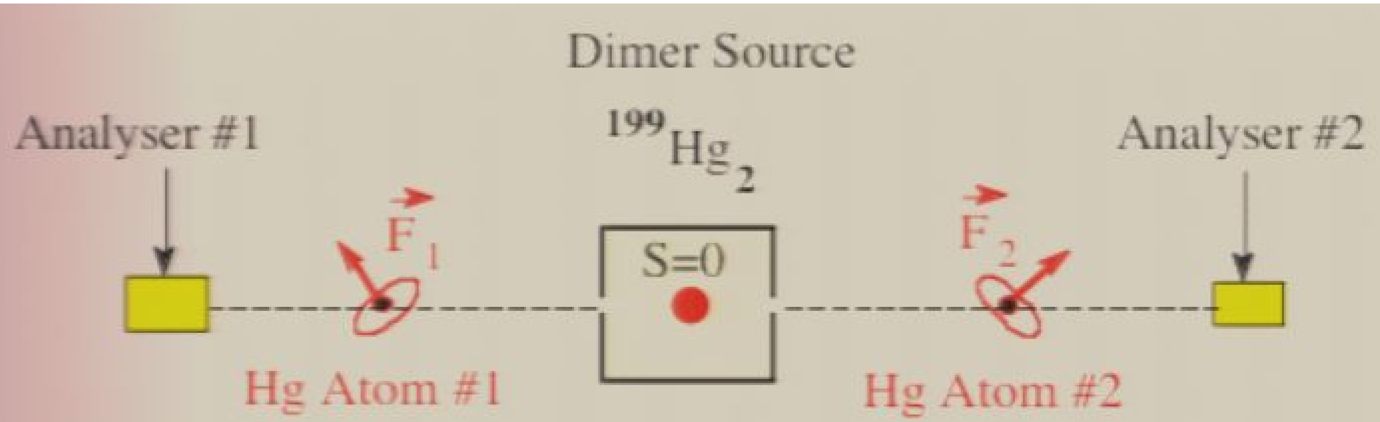

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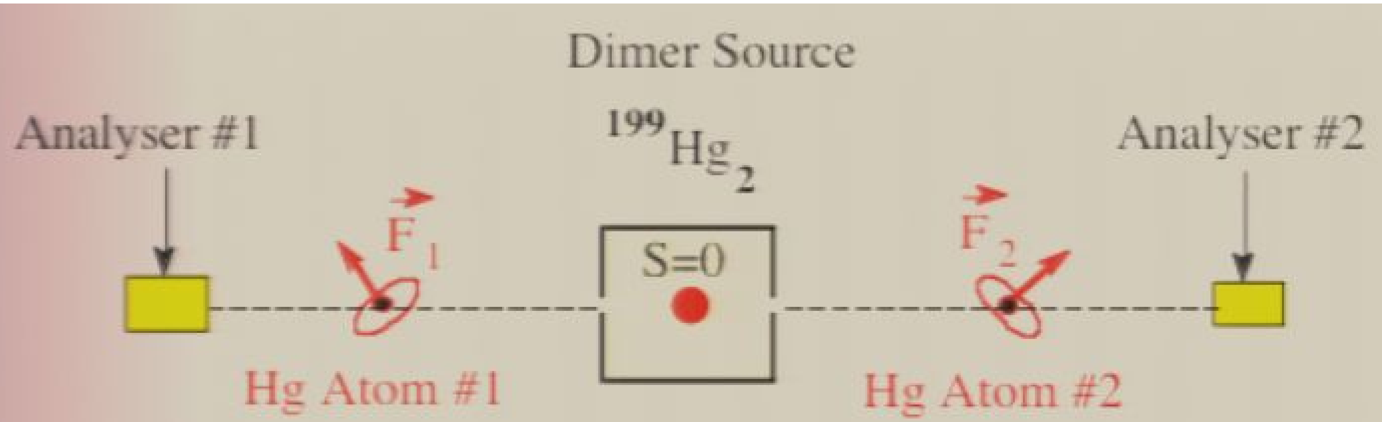

$J=0$ $\qquad I=\frac{1}{2}$ $\qquad F=I+J=\frac{1}{2}$

$$|\Psi\rangle \equiv \frac{1}{\sqrt{2}}\left\{\begin{pmatrix}1\\0\end{pmatrix}_1\begin{pmatrix}0\\1\end{pmatrix}_2-\begin{pmatrix}0\\1\end{pmatrix}_1\begin{pmatrix}1\\0\end{pmatrix}_2\right\}$$

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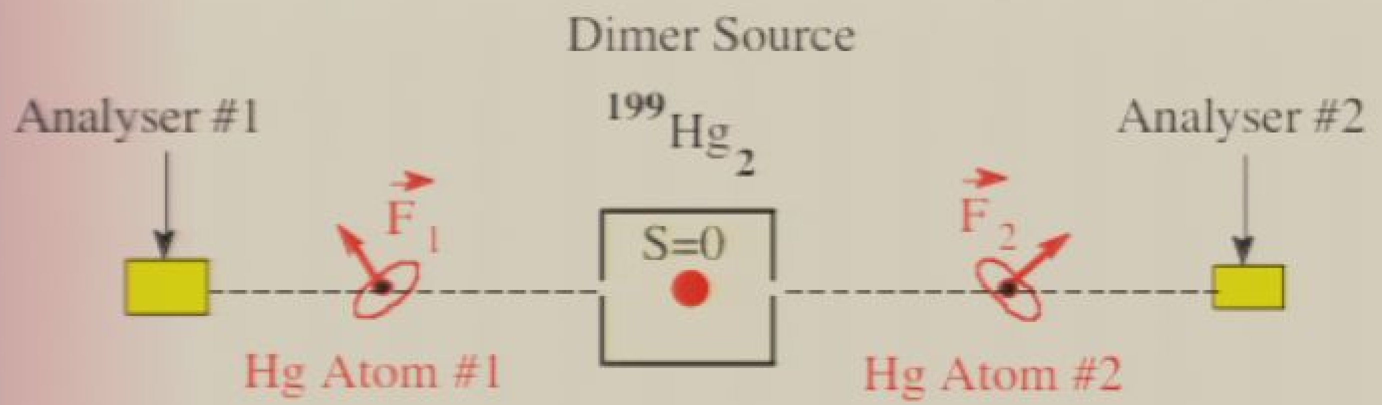

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Analyzers determine component of F in a specific direction.

Measure correlations between different components of F.

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Hg Isotopes
(natural abundance)

^{196}Hg	0.15%	I=0
^{198}Hg	10.1%	I=0
^{199}Hg	16.84%	I=1/2
^{200}Hg	23.1%	I=0
^{201}Hg	13.22%	I=3/2
^{202}Hg	29.65%	I=0
^{204}Hg	6.8%	I=0

In a mercury dimer source, we have

$^{199}Hg_2$

with 2.84% abundance.

DIMER

DISSOCIATION

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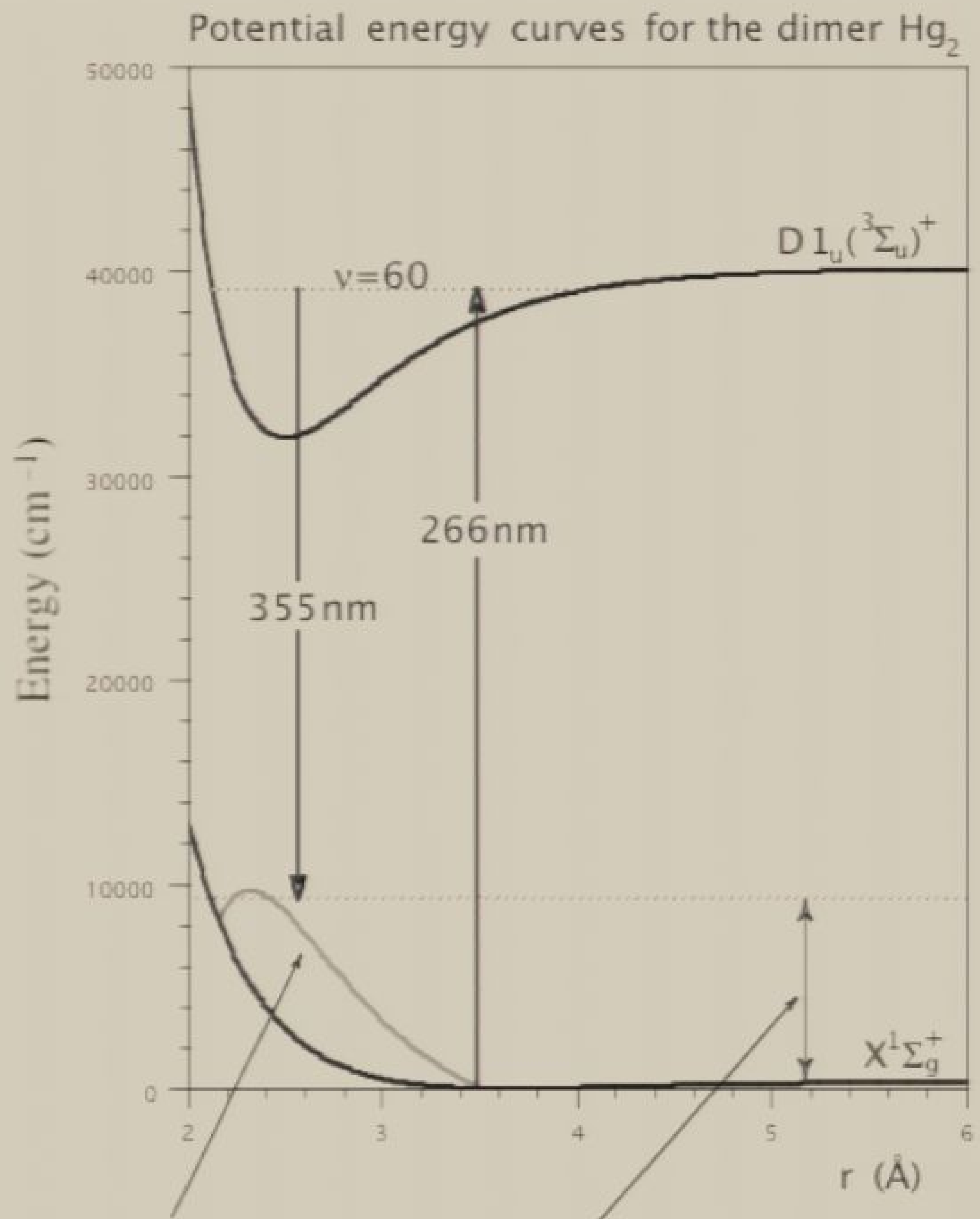

Mulliken Diff.Pot.

1.17eV $\Rightarrow$ v=753m/sec

We require $^{199}Hg_2$ in a nuclear spin singlet

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T e x a s A & M

P h y s i c s

We require $^{199}Hg_2$ in a nuclear spin singlet

^{199}Hg has total spin 1/2 $\Rightarrow$ fermion

Thus, the Pauli Principle $\Rightarrow$ $P\Psi = -\Psi$

where P is the particle exchange operator

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$$P\Psi = (\sigma_{el} i_{el} \Psi^{el})\, \Psi^{vib}\, (C_2 \Psi^{rot})\, (p_{nuc} \Psi^{nuc})$$

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g $\Rightarrow$ reflection symmetry, σ_{el}, of the e^- wave function

+ $\Rightarrow$ inversion symmetry, i_{el}, of the e^- wave function

$$\sigma_{el} \Psi^{el} = +\Psi^{el}; \qquad i_{el} \Psi^{el} = +\Psi^{el}; \qquad C_2 \Psi^{rot} = (-1)^J\, \Psi^{rot};$$

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T e x a s A & M P h y s i c s

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Nuclear spin singlet:

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Thus, J must be an even integer.

In the nuclear spin singlet state, the rotational states must have even J:

$$J=0, 2, 4, \ldots$$

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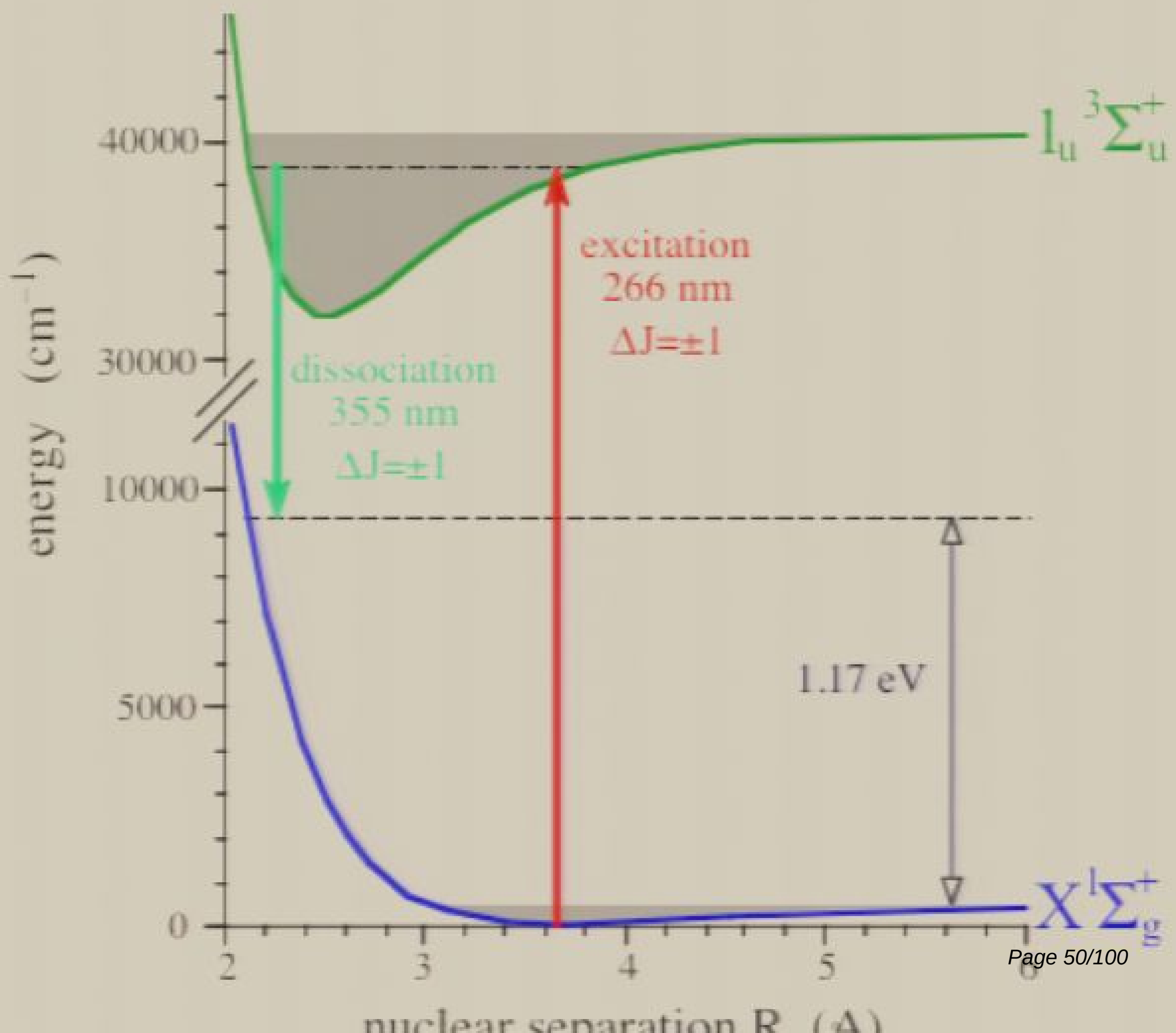
J=1, 3, 5

T e x a s A & M   P h y s i c s

Since $^{199}Hg_2$ is a homonuclear molecule, each leg of the Raman transition can only have ΔJ=±1; ΔJ cannot be 0.



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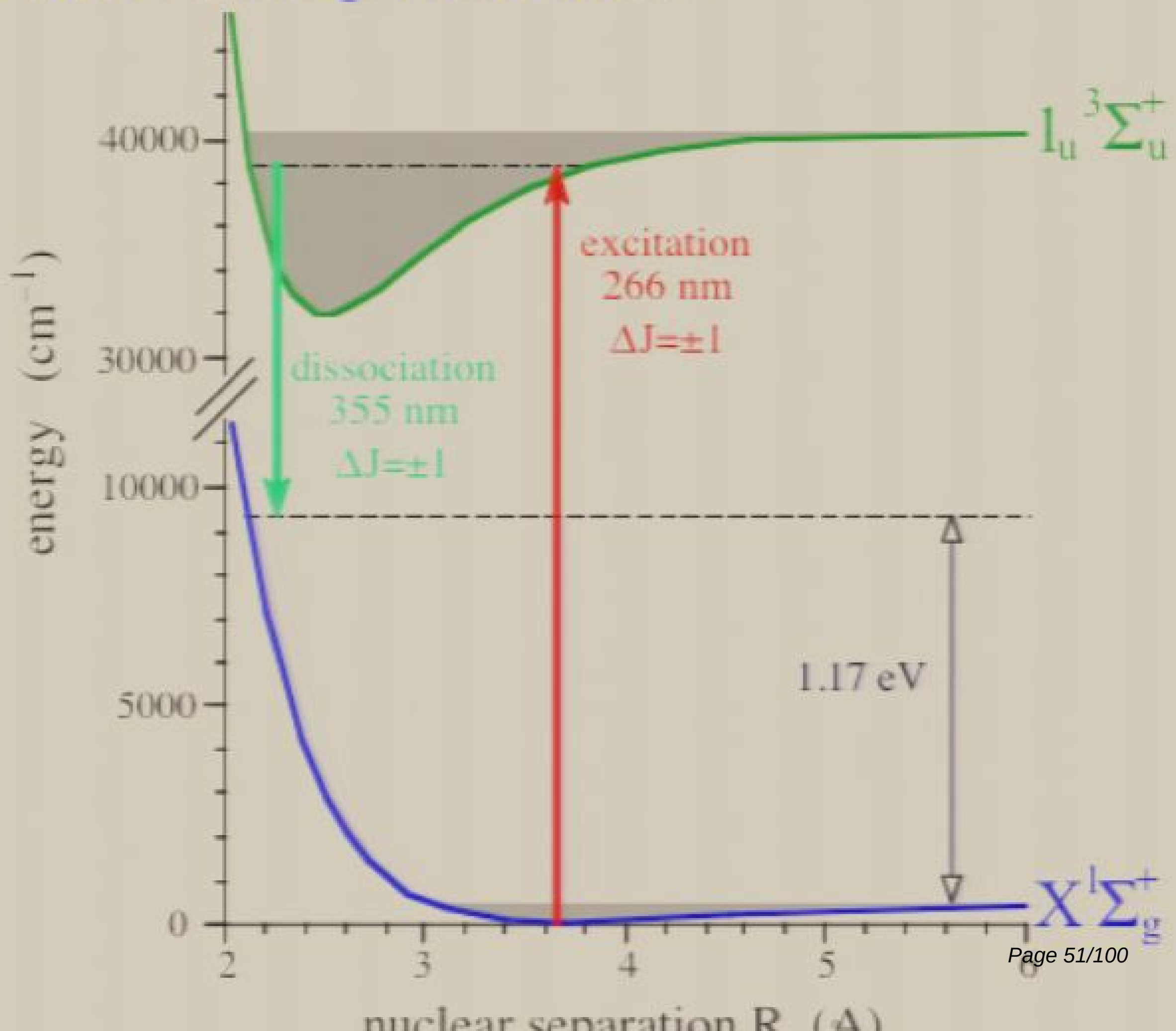

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Simulated Dimer Spectra

$$X\,{}^1\Sigma_g^+ \leftarrow D\,1_u\,{}^3\Sigma_u^+ \qquad \nu = 60$$

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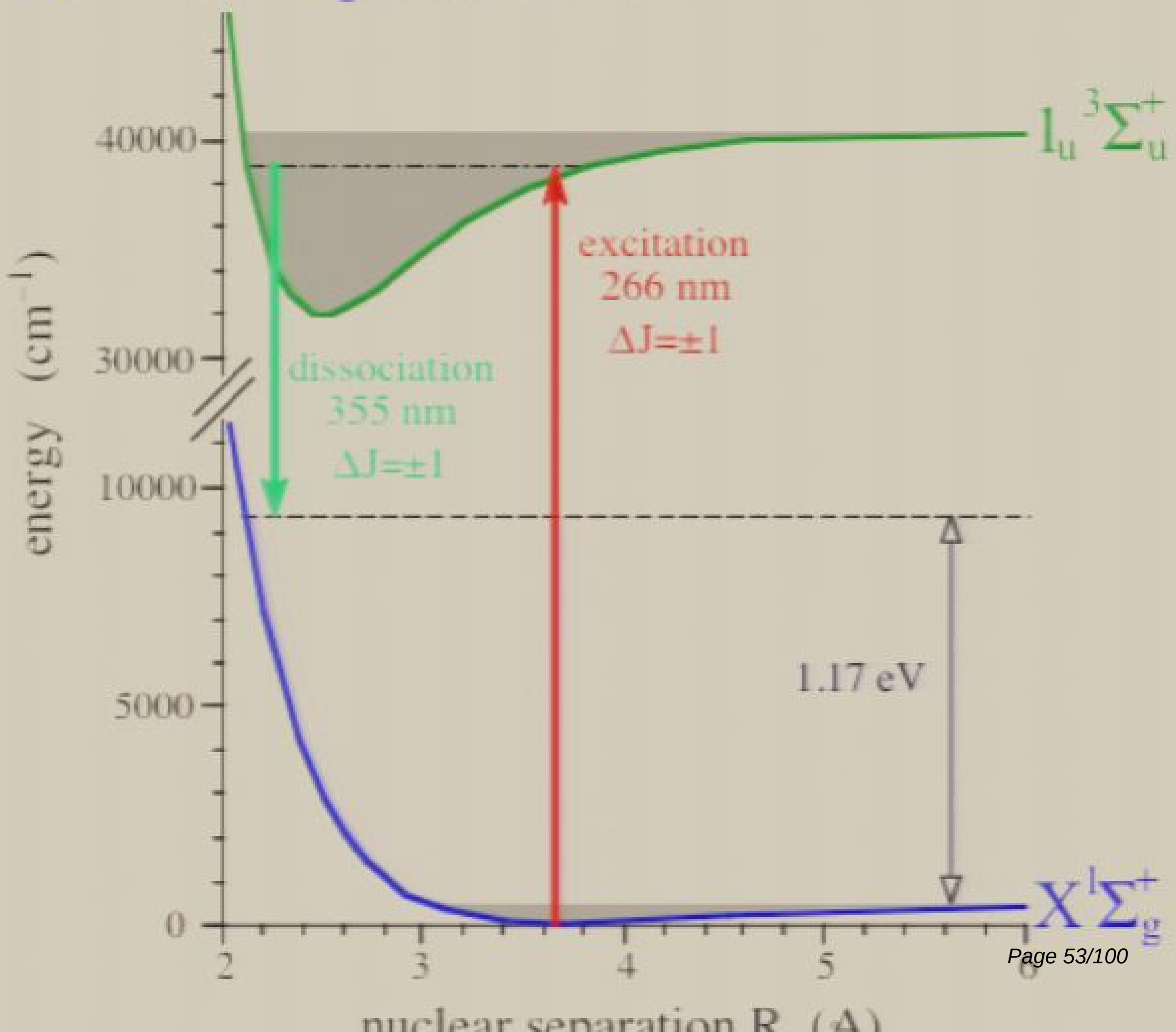

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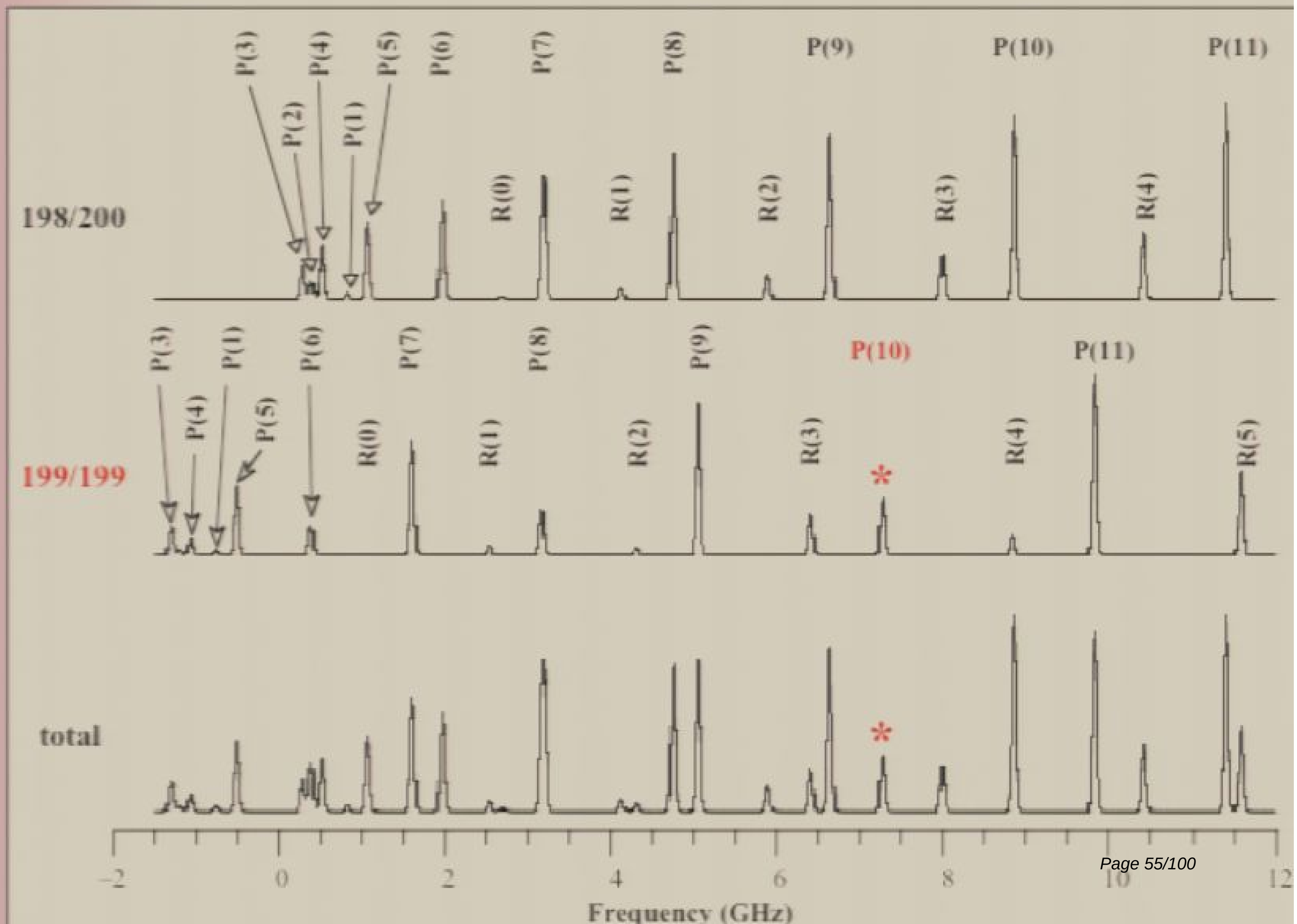

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Preliminary Dimer Spectra Data

Mass 398 isotopomer $X\,^1\Sigma_g^+ \leftarrow D\,1_u\,^3\Sigma_u^+$ $\nu = 6($

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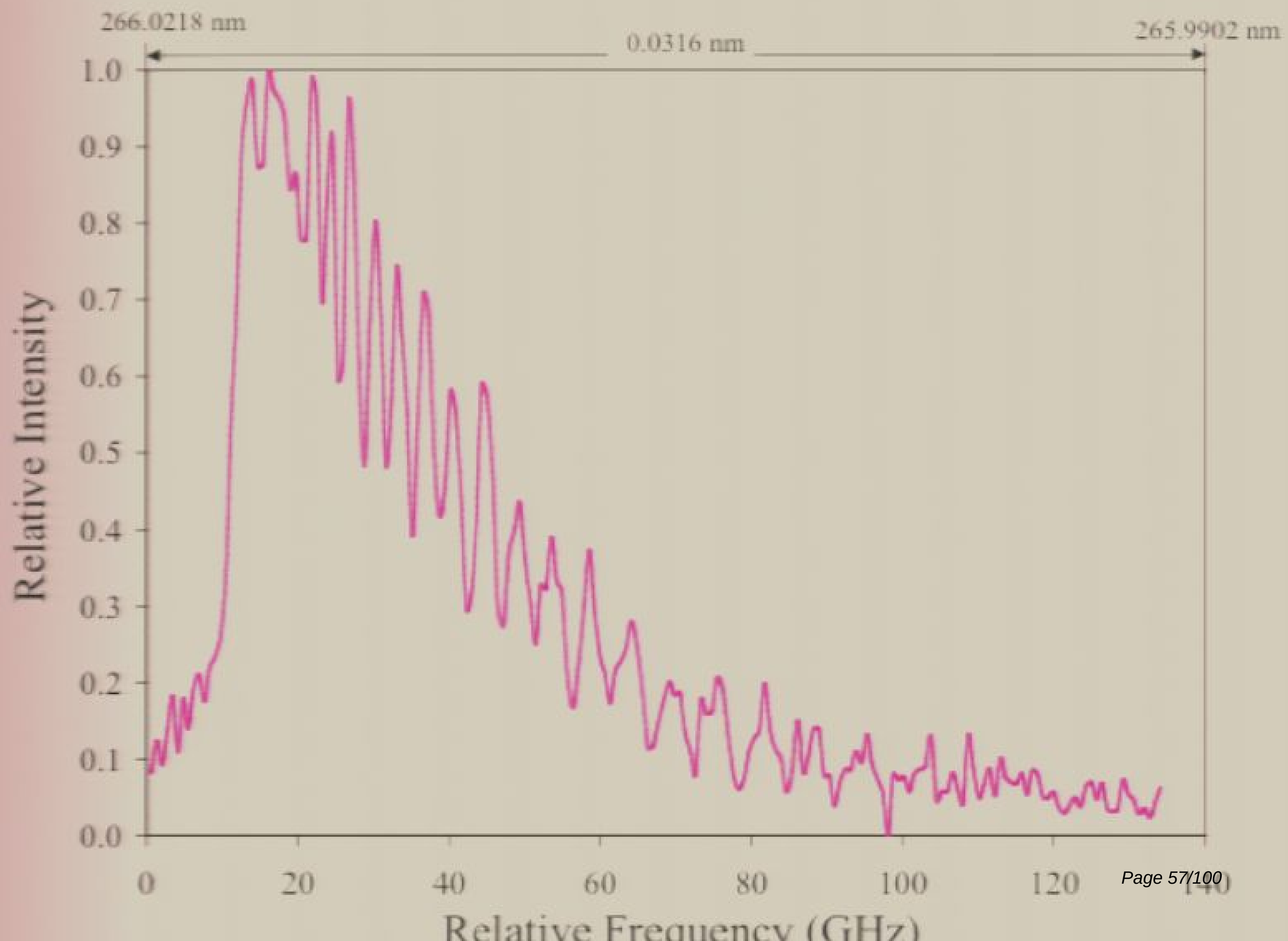

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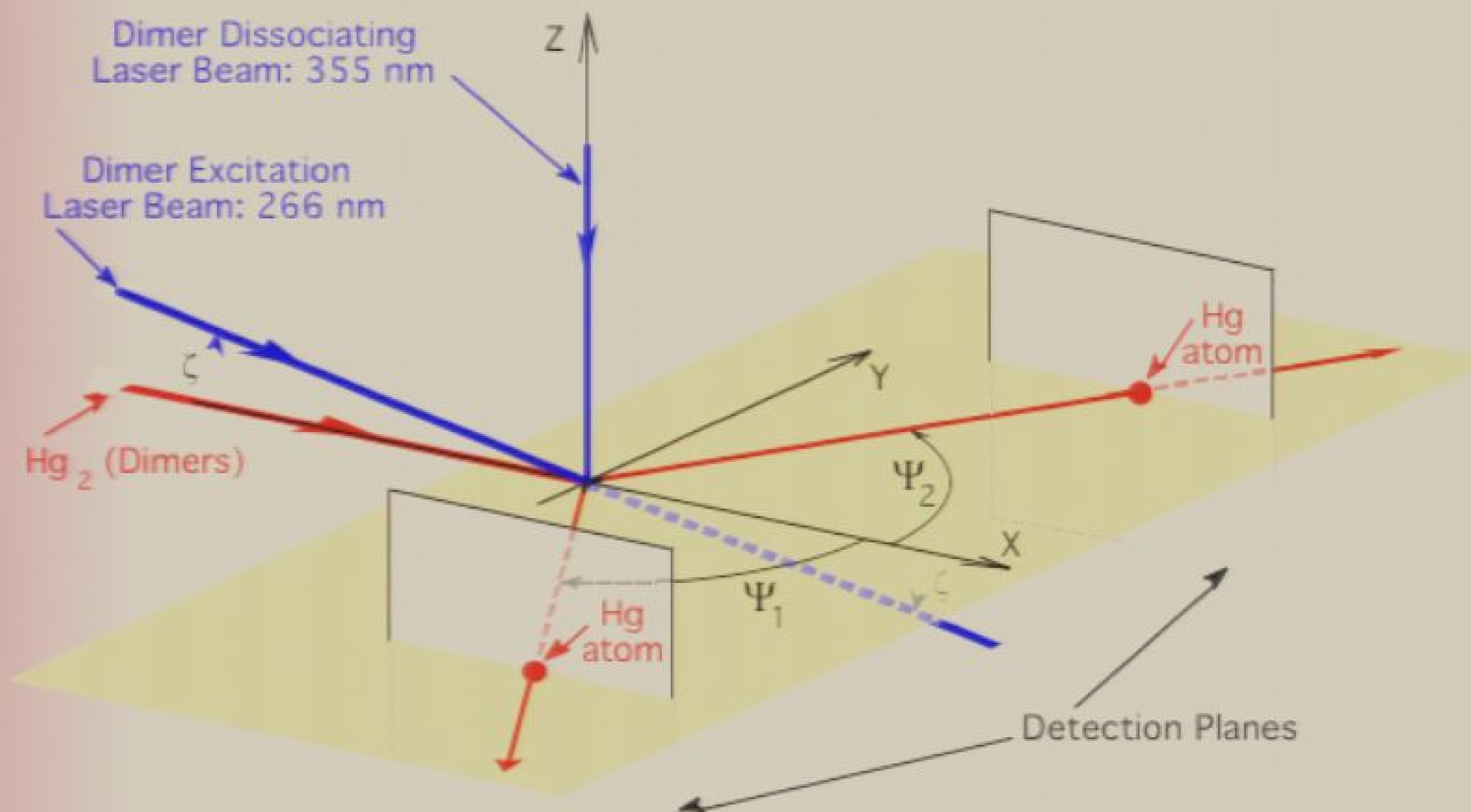

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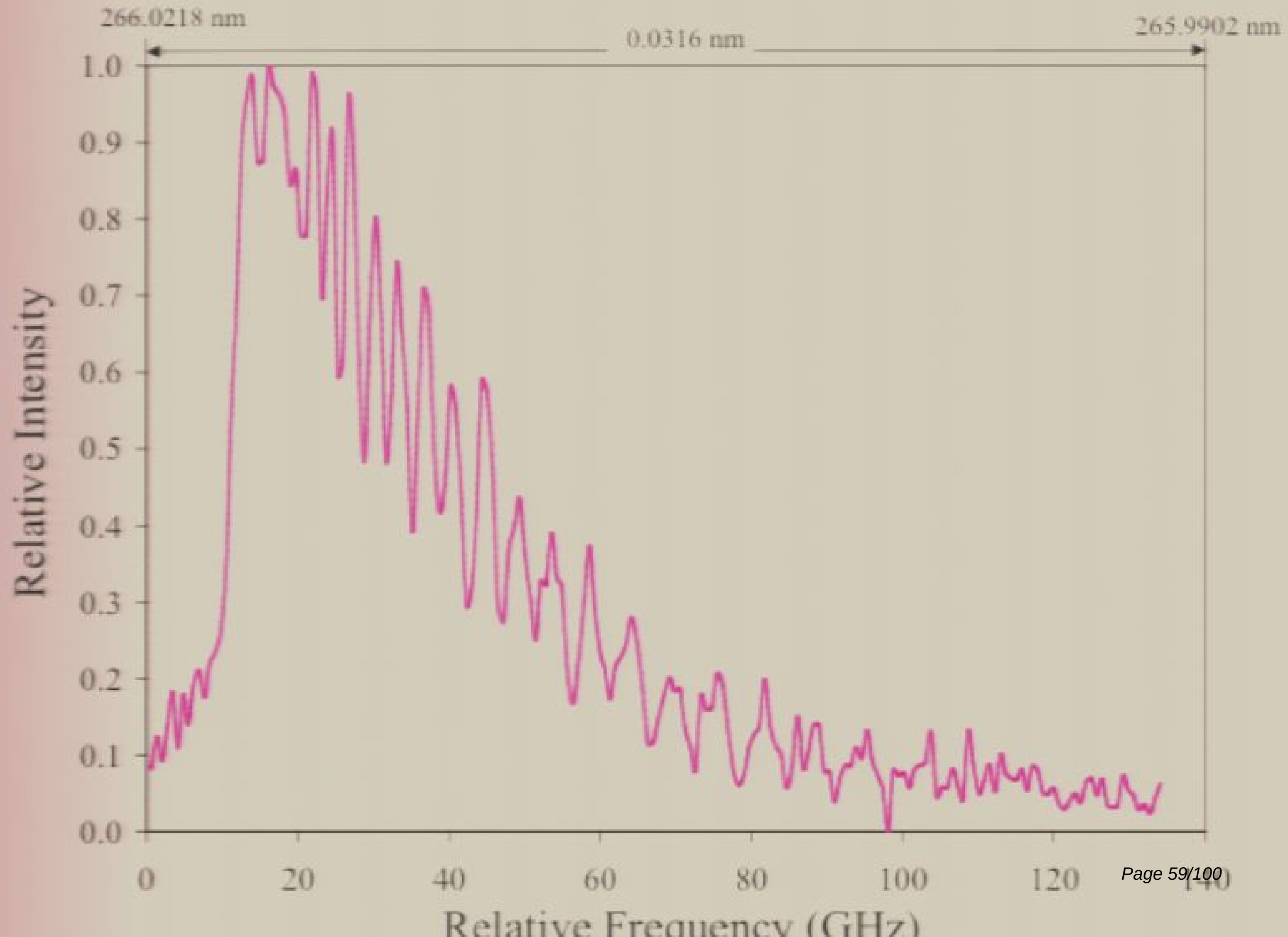

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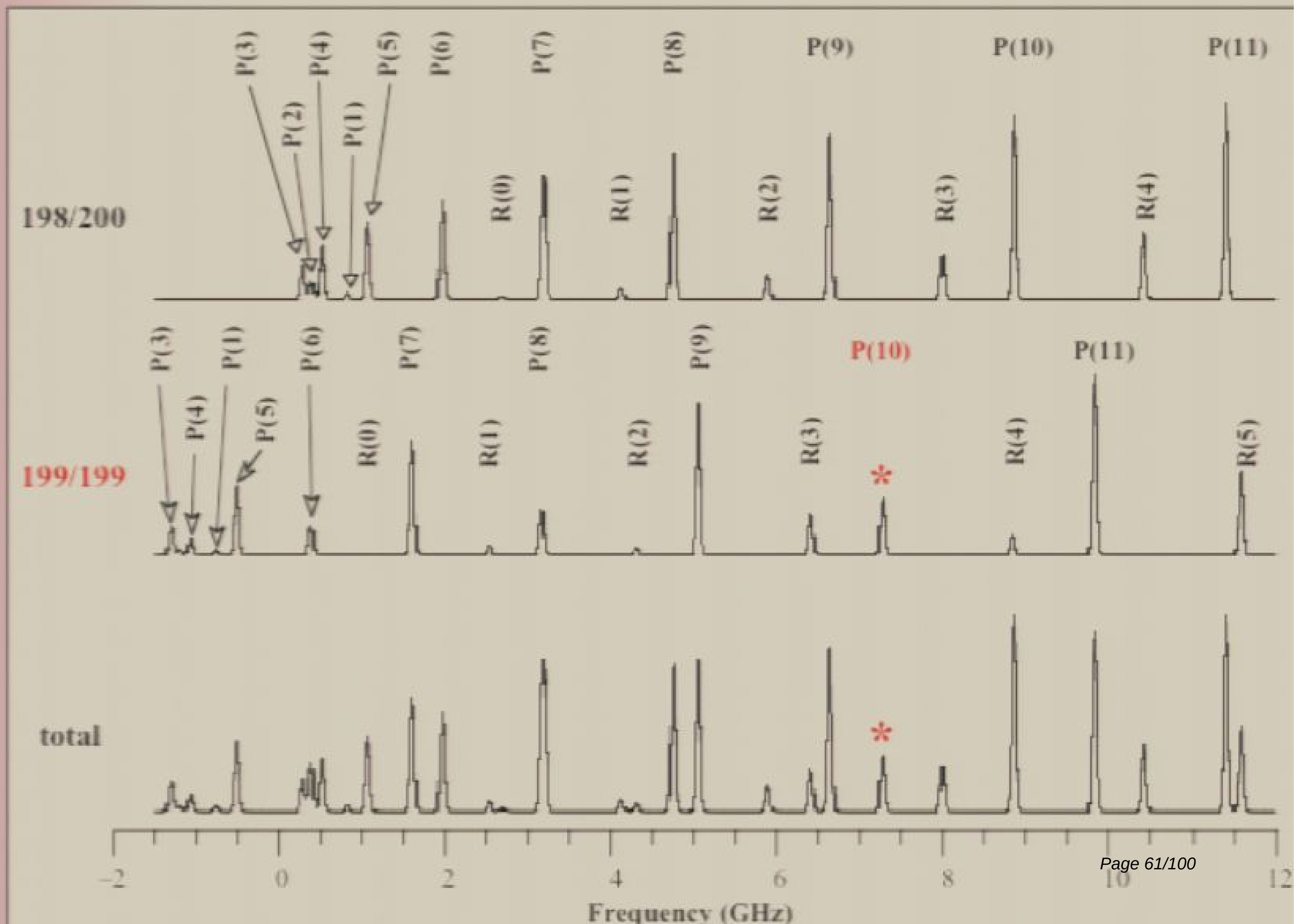

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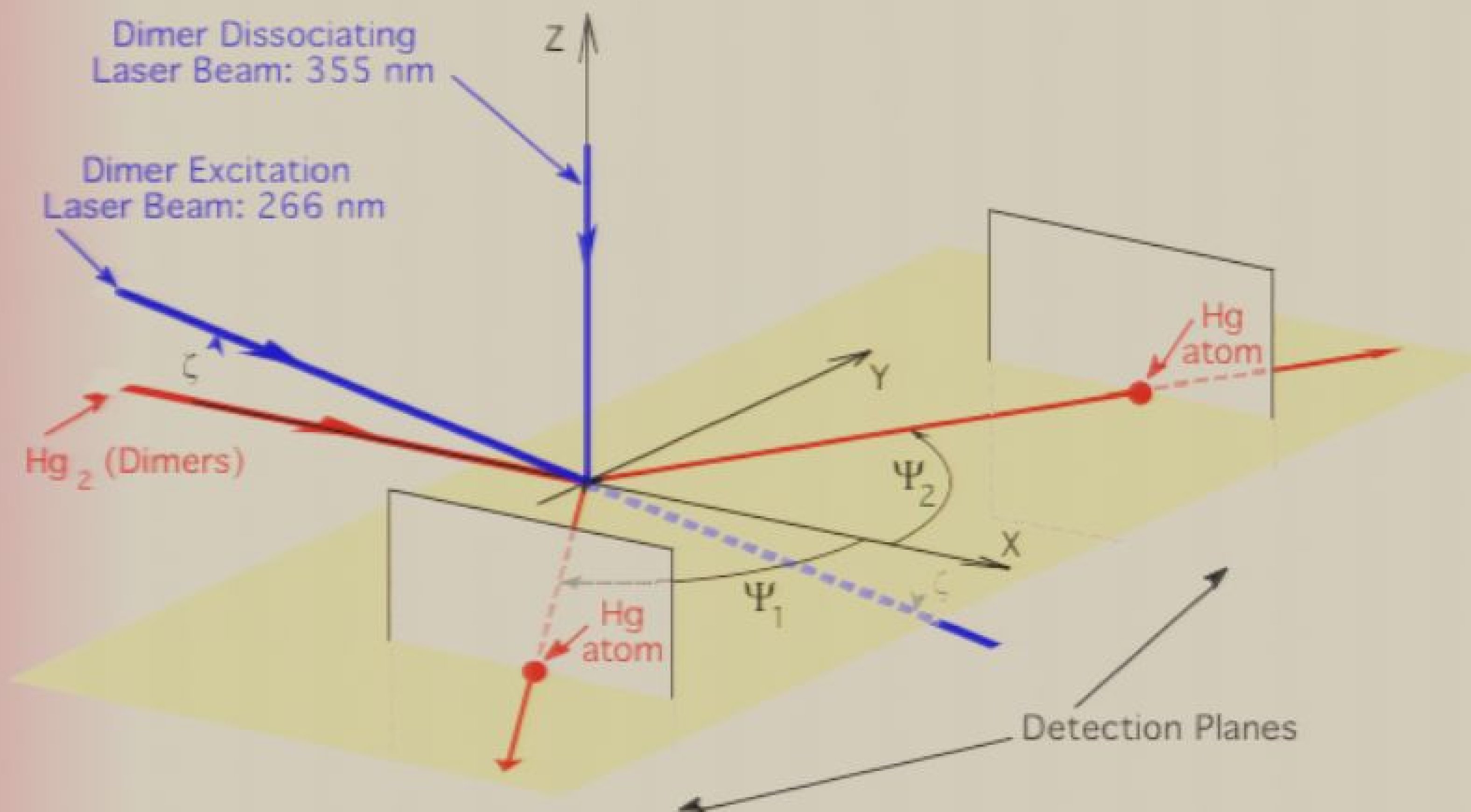

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Dissociation Lasers

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Dissociation Lasers

263 – 269 nm System

Alexandrite Laser

150 ns FWHM pulses

4 MHz linewidth

40 mJ fundamental

Developed high voltage ramp/Q-switch combination to cancel chirp. Narrowest linewidth of existing pulsed lasers?

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355 nm System

Excimer pumped dye laser

15 ns FWHM pulses
6 GHz linewidth
4 mJ

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MERCURY ATOM

EXCITATION

&

IONIZATION

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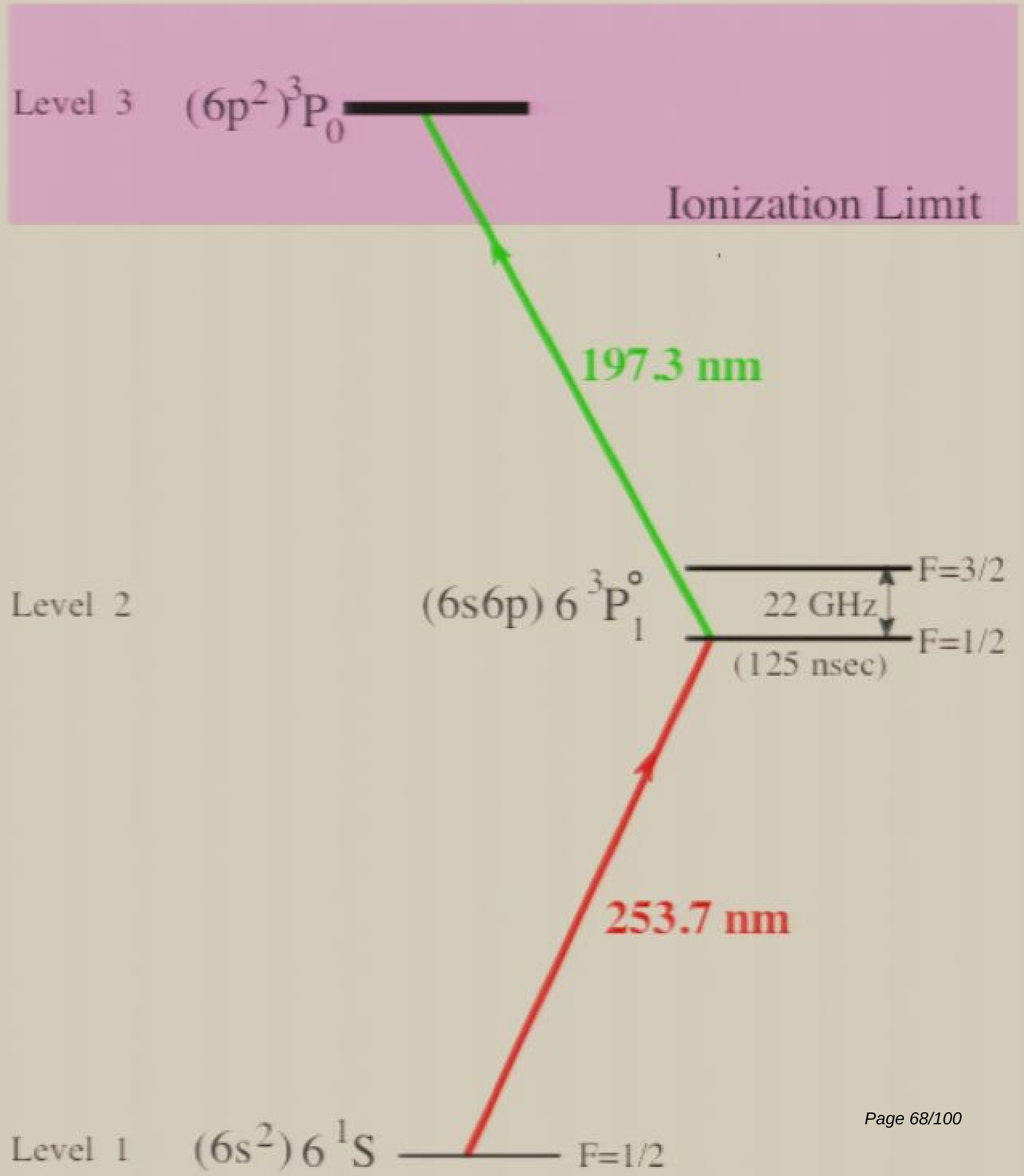

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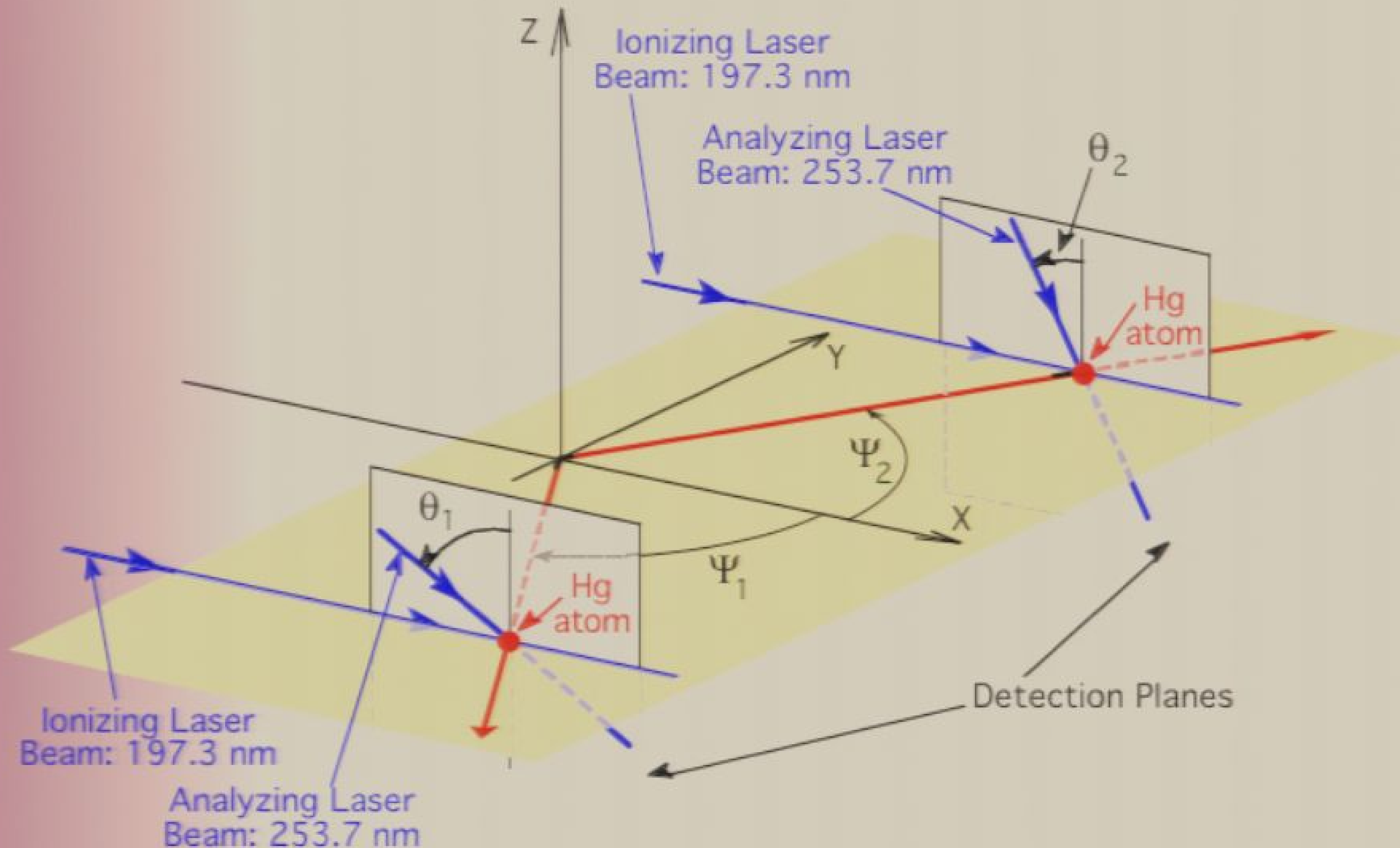

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Auto-ionizing transition:

Linewidth $(6p^2)^3P_0$:

Γ=9 cm^{-1}=270 GHz

Oscillator Strength (calculated):

f=0.362

Absorption Cross-section:

$\sigma=2.3\times10^{-14}$ cm^2

Radiative lifetime:

τ_r=0.5 nanosec

Non-radiative lifetime:

τ_i=3.7 picosec

Pulse energy to saturate transition:

E≈100 μJ

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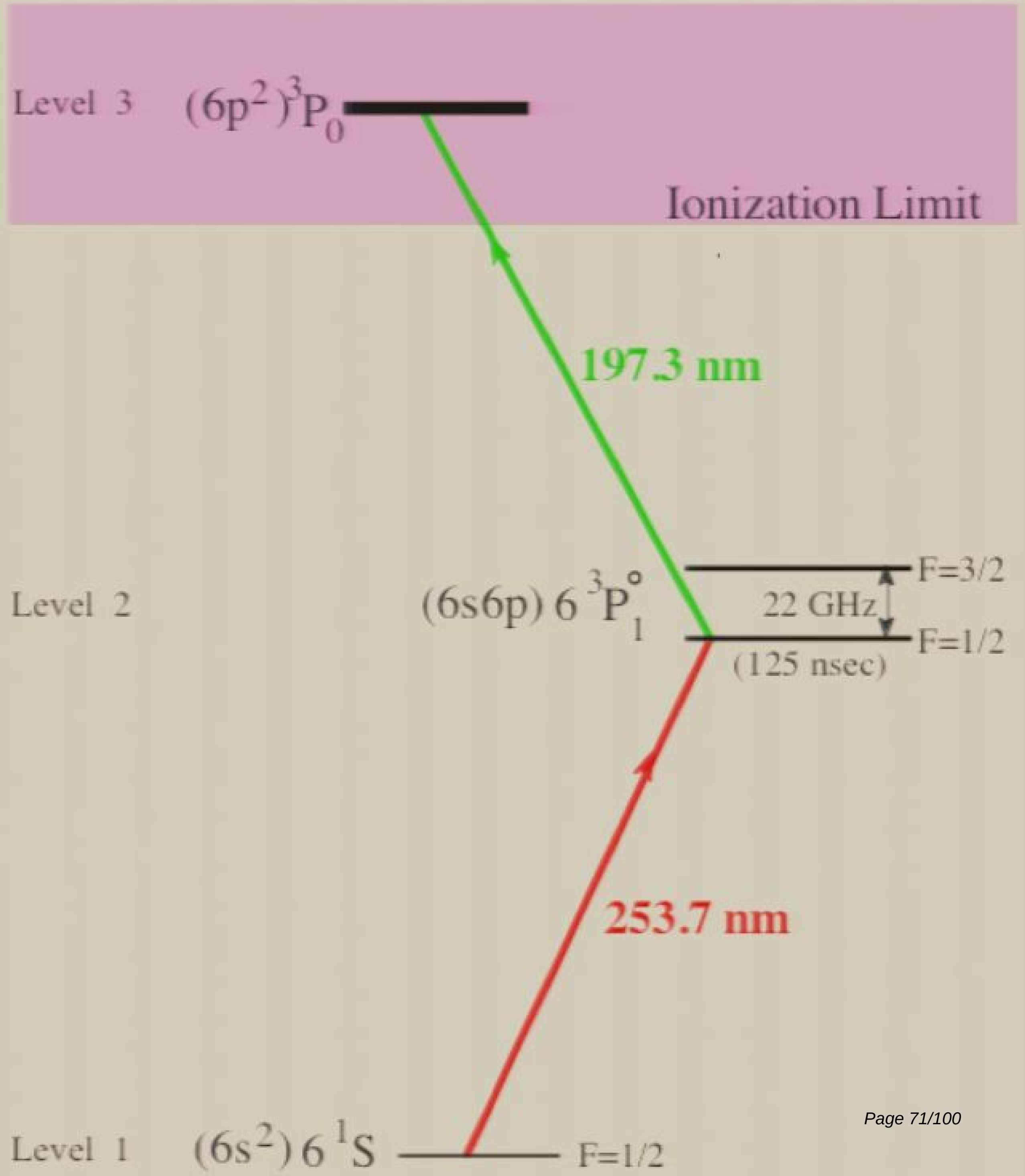

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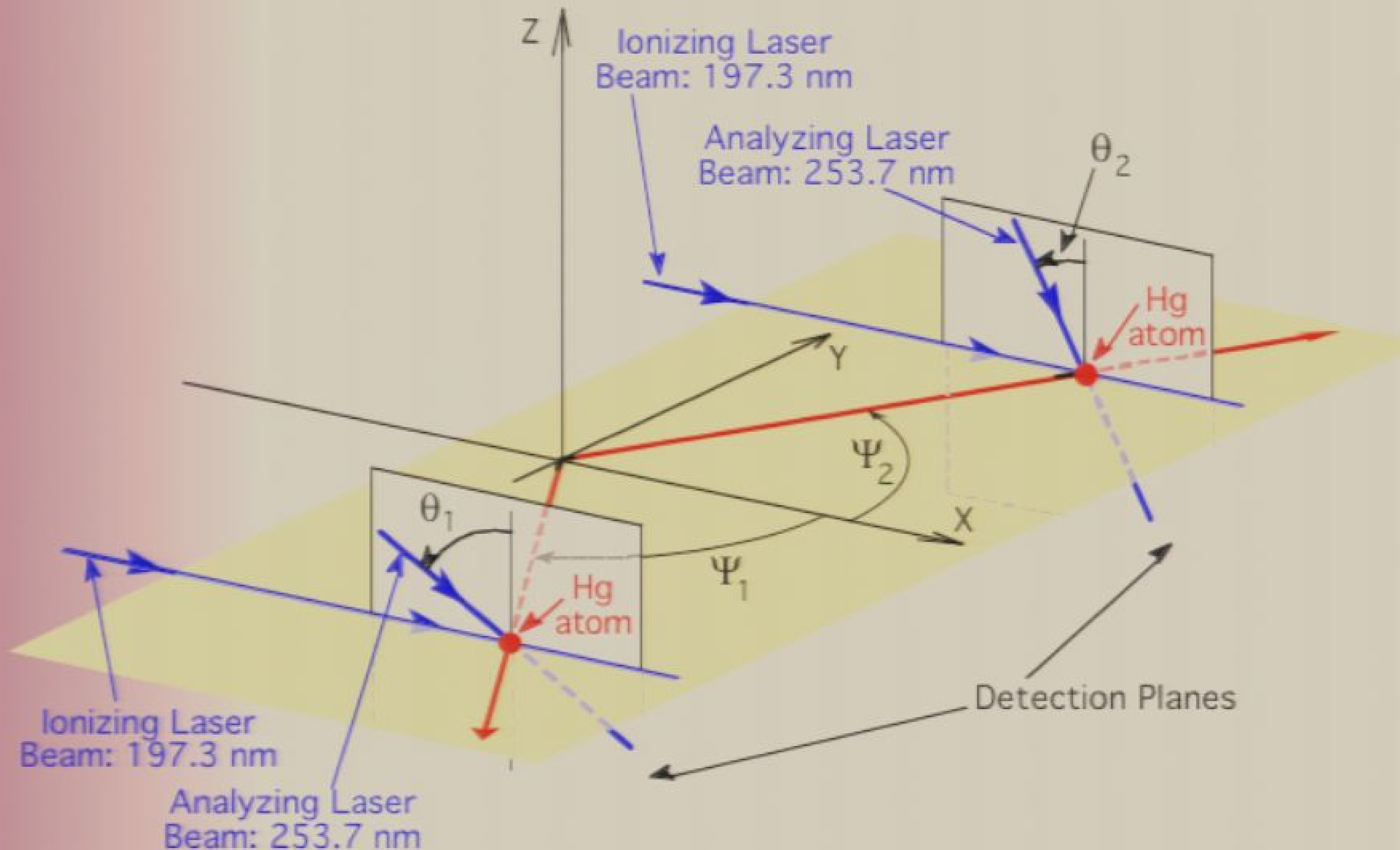
MERCURY ATOM

EXCITATION

&

IONIZATION



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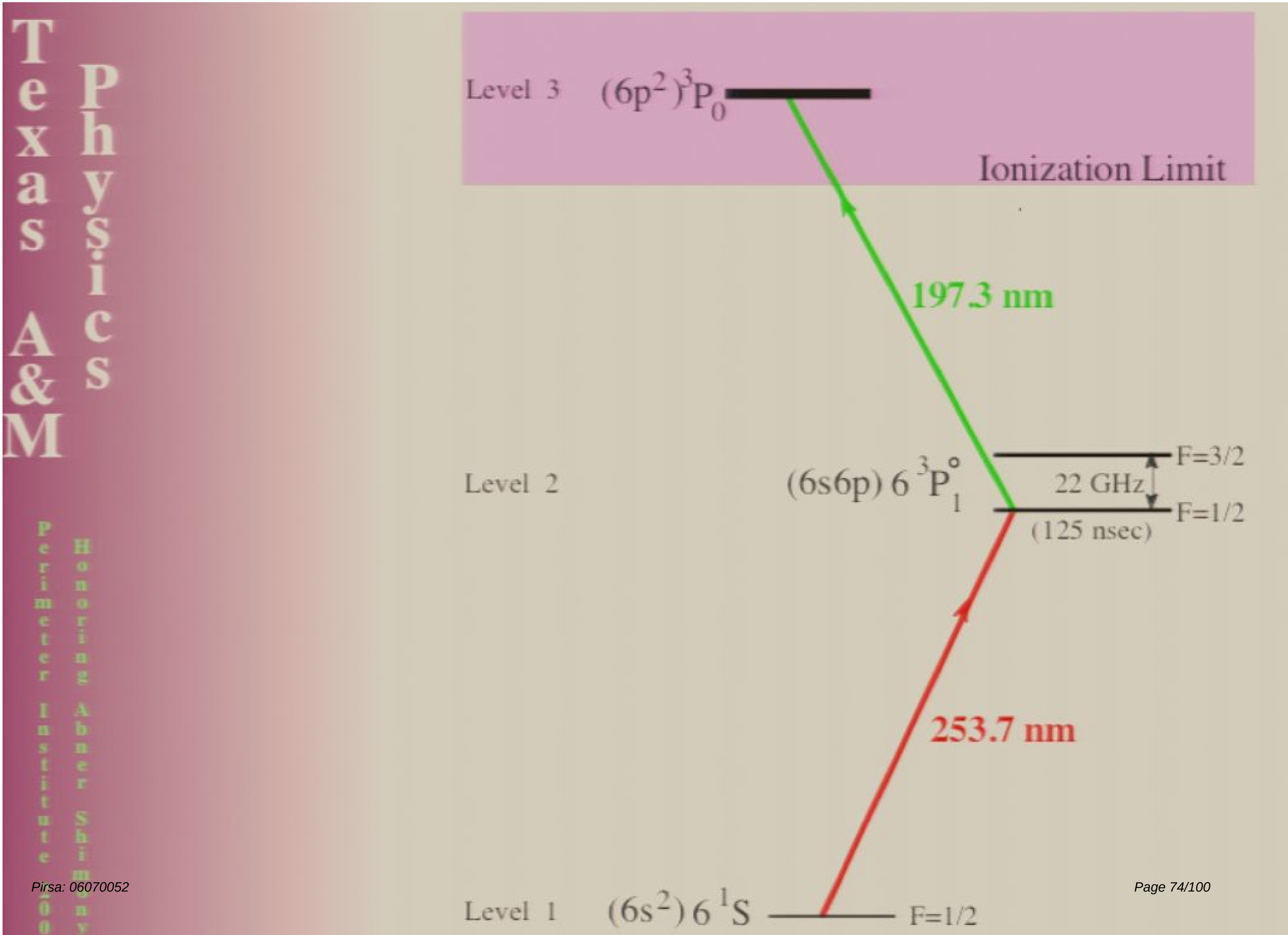
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Level 3 $(6p^2)\,^3P_0$
Ionization Limit
197.3 nm
Level 2 $(6s6p)\,6\,^3P^\circ_1$
F=3/2
22 GHz
F=1/2
(125 nsec)
253.7 nm
Level 1 $(6s^2)\,6\,^1S$
F=1/2

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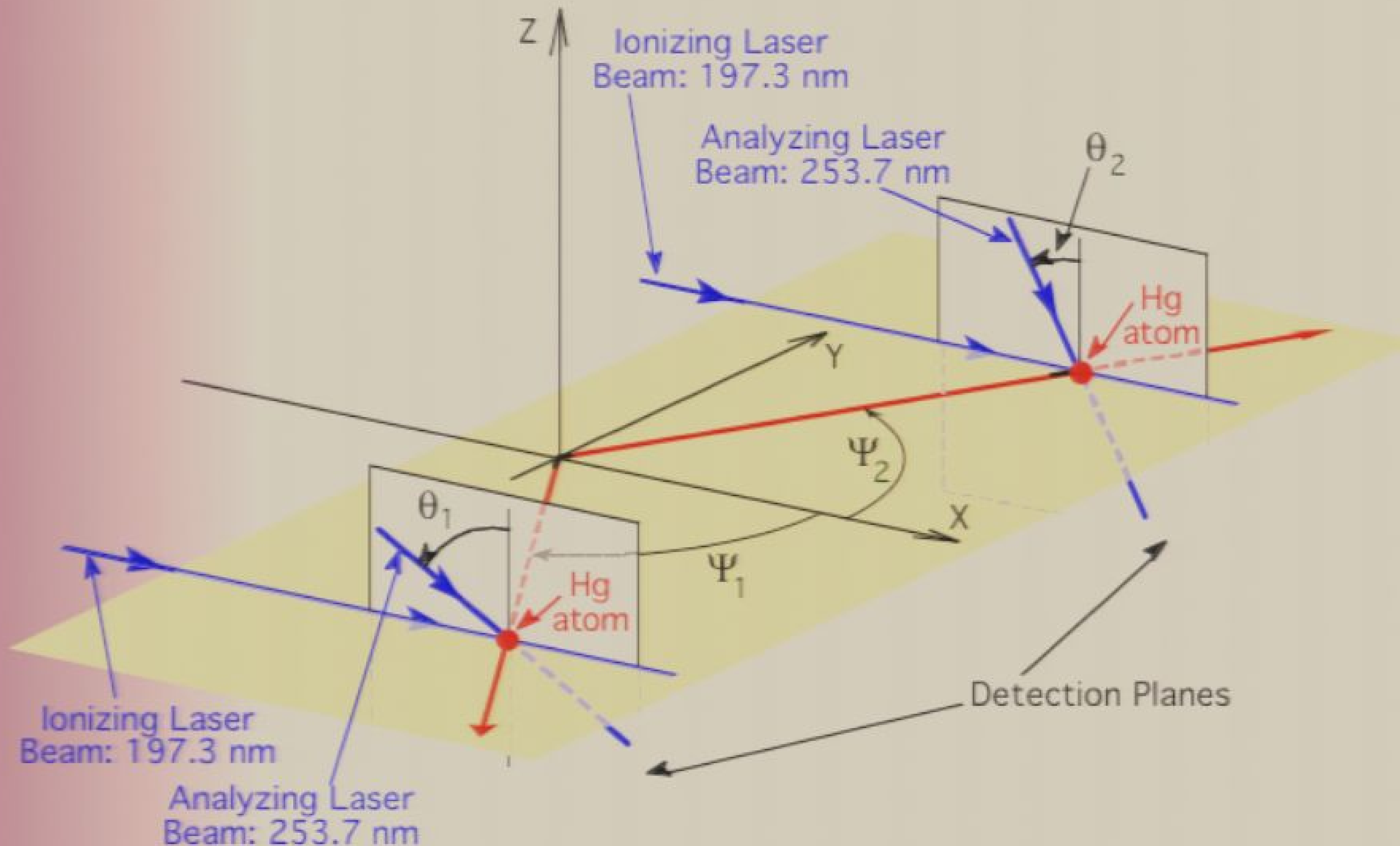

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Radiative lifetime:

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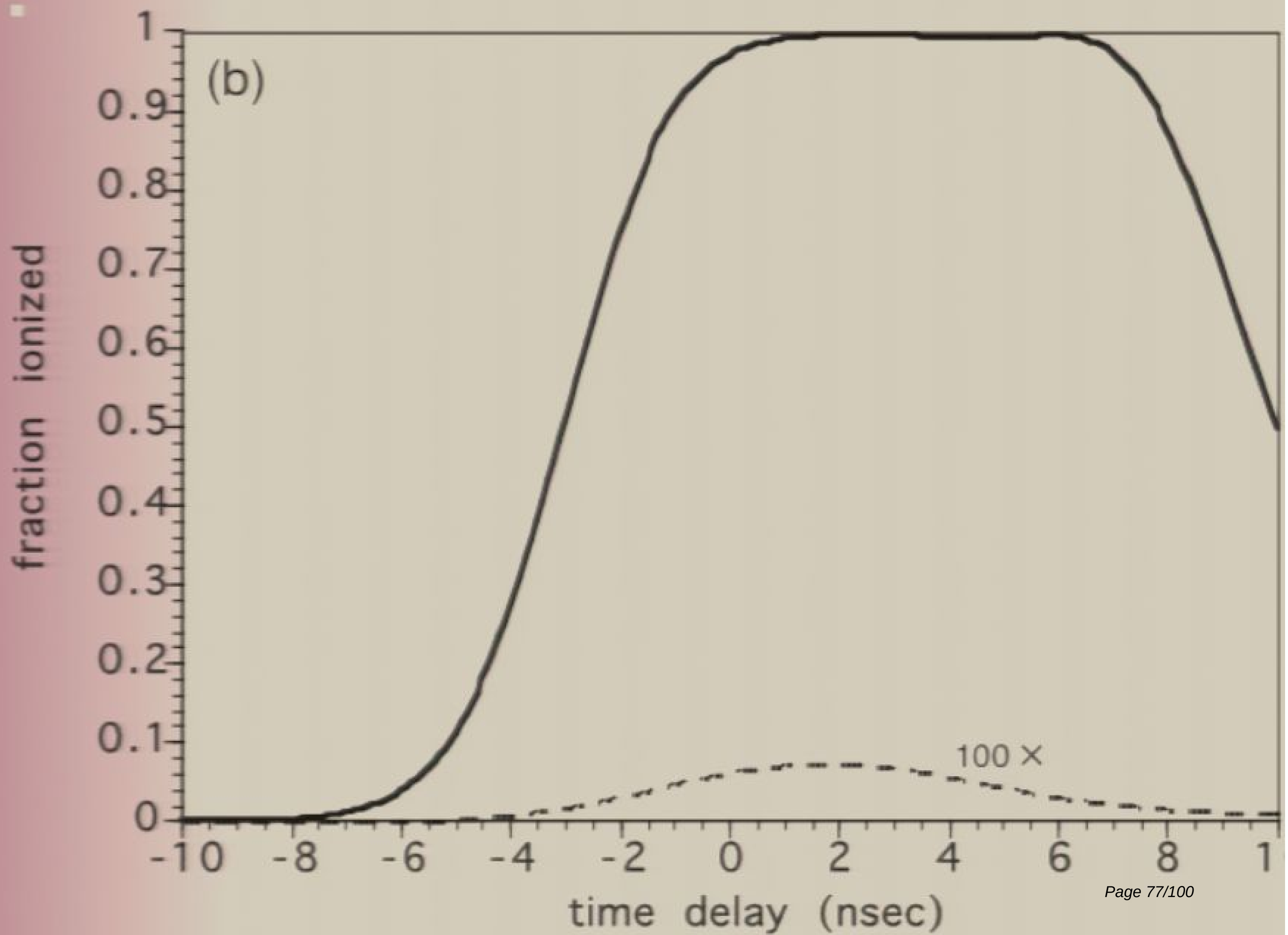
Non-radiative lifetime:

τ_i=3.7 picosec

Pulse energy to saturate transition:

$E\approx100\ \mu J$

Ionization Fraction



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Excitation/Ionization Lasers

253.7 nm: 3rd harmonic of 761.1 nm;

197.3 nm: 4th harmonic of 789.2 nm

761.1 nm and 789.2 nm are produced simultaneously by a flashlamp pumped Ti:Sapphire laser.

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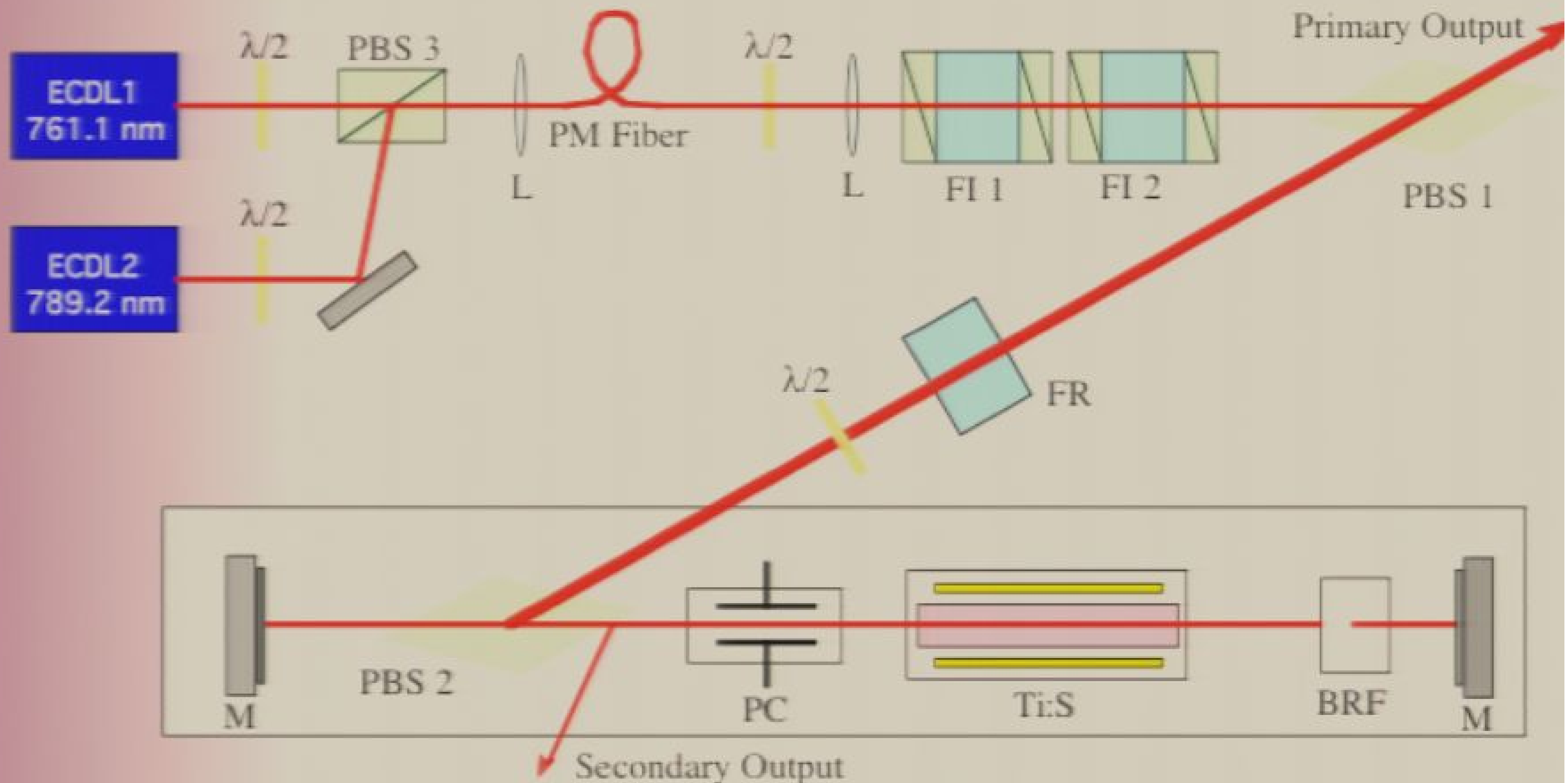
Dual frequency Ti:Sapphire Laser



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MERCURY

ATOM

DETECTION

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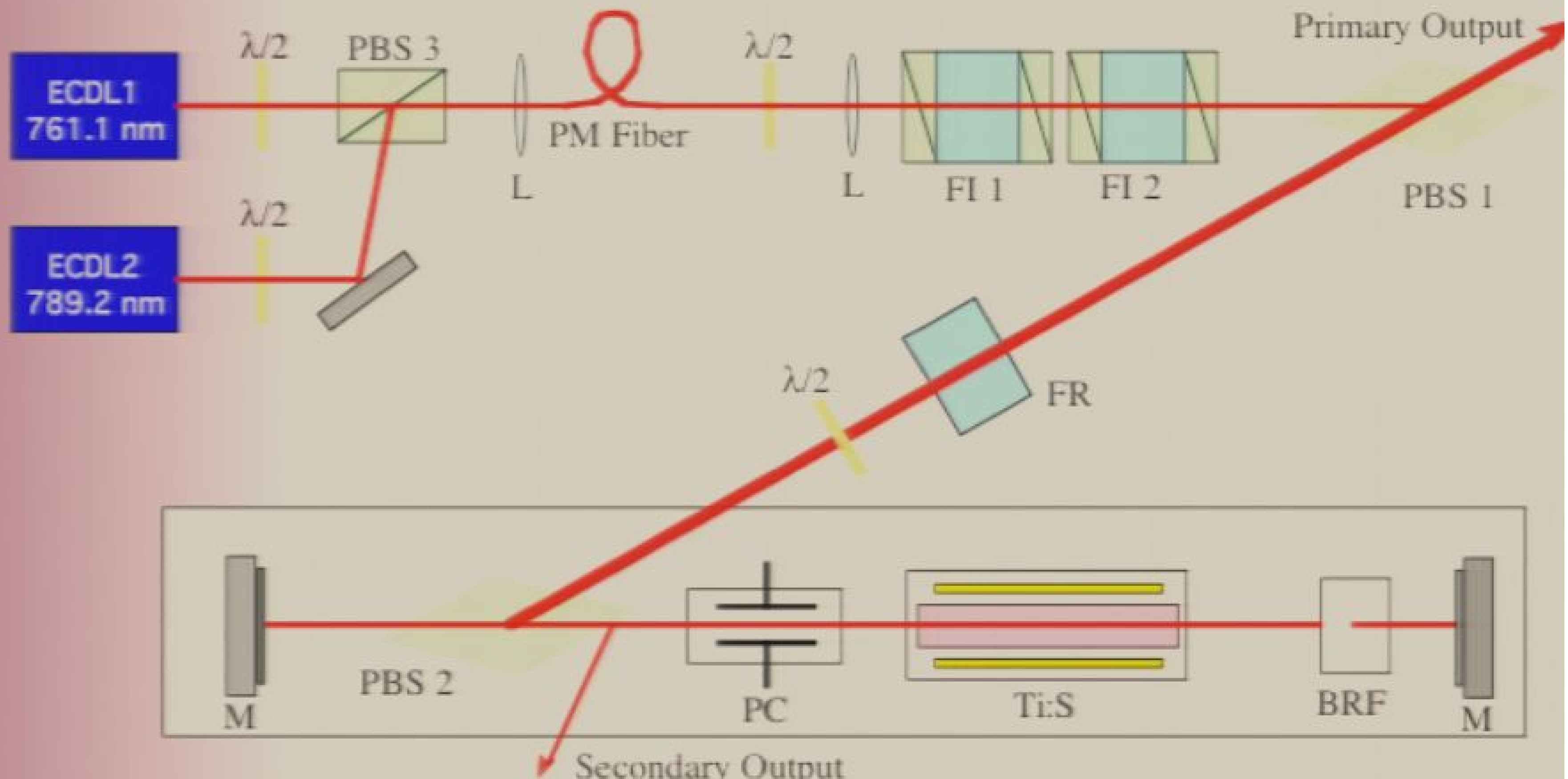
Dual frequency Ti:Sapphire Laser



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MERCURY

ATOM

DETECTION

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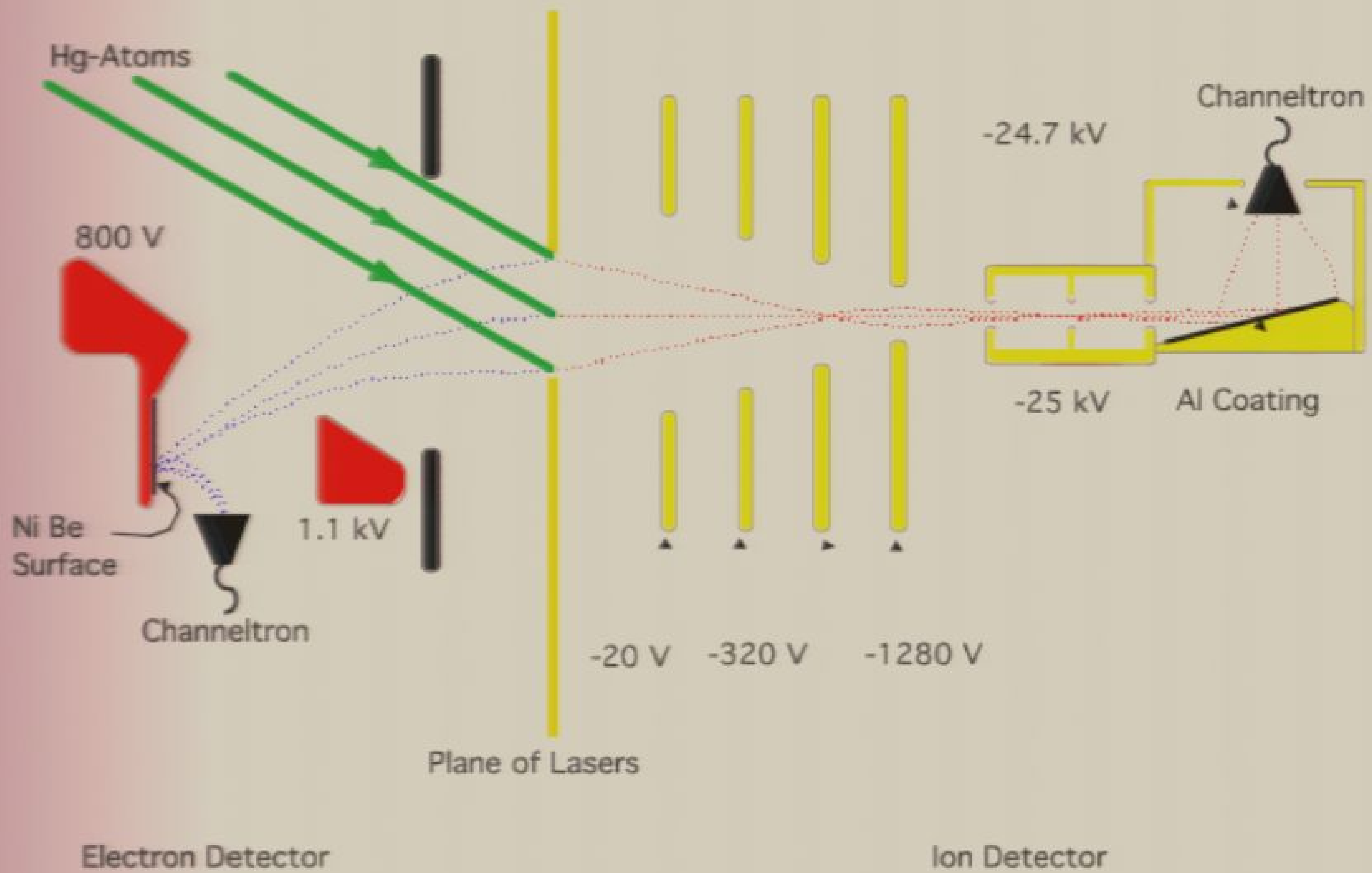

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NUCLEAR

SPIN

ANALYSIS

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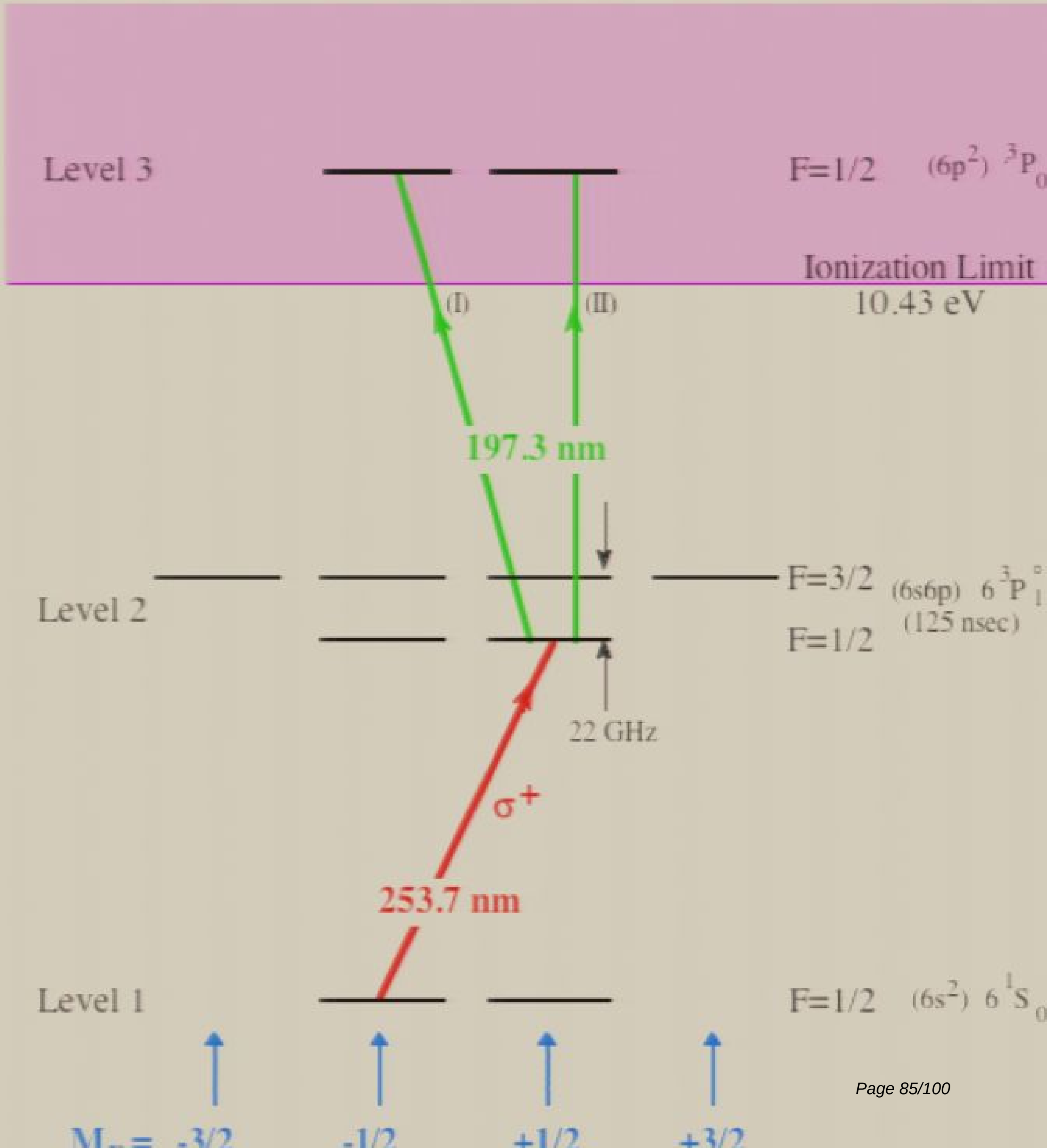

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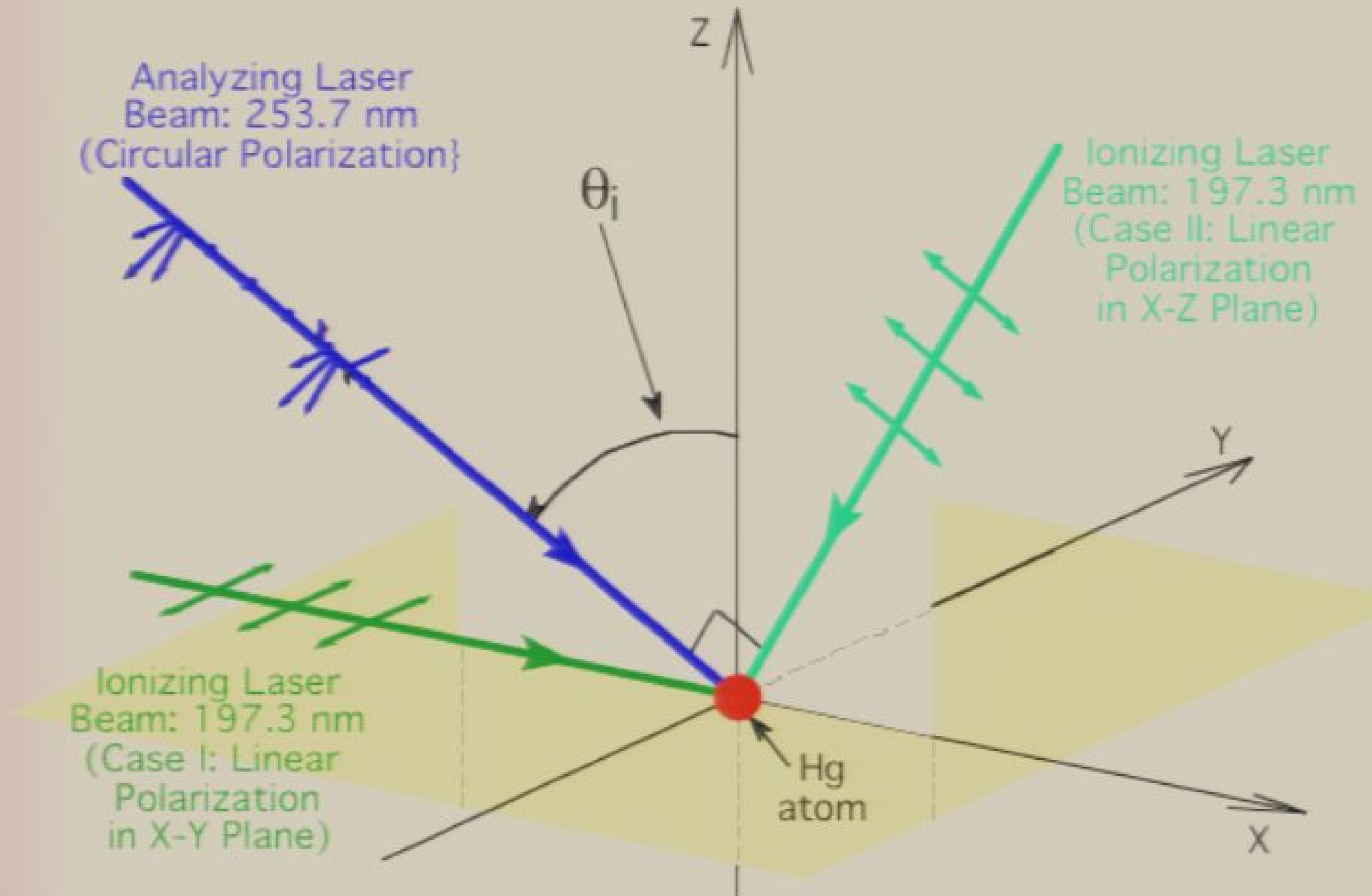

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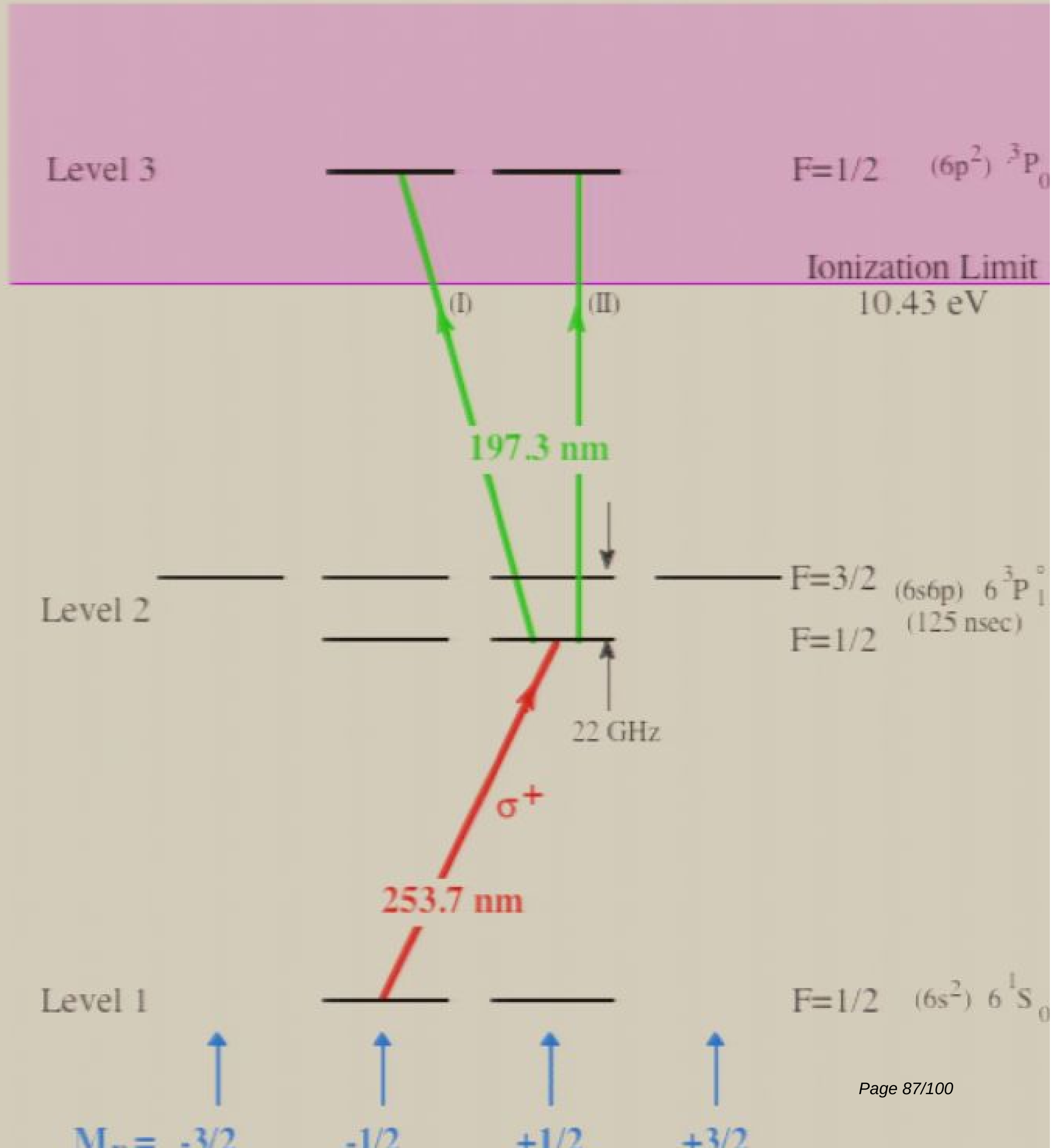

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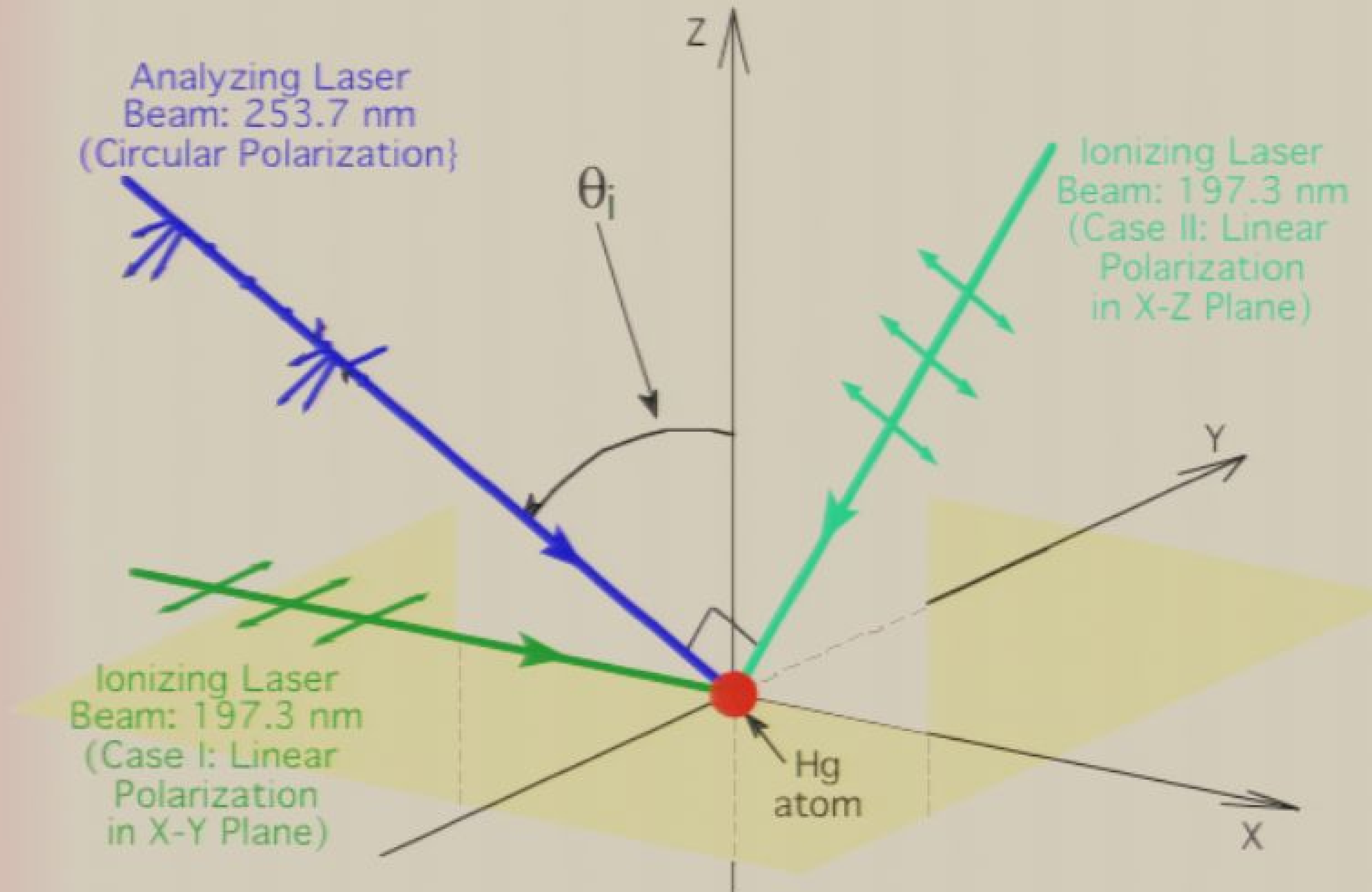

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QUANTUM

MECHANICAL

PREDICTIONS

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One may choose various quantities for the correlation measurement.

Consider the case of measuring the component $M_F = +\frac{1}{2}$ of both atoms in various directions.

Quantum Predictions

$$R_{++}(\theta_1,\theta_2) = g\eta^2 N\left[\frac{1}{4} - \frac{1}{4}\mathrm{Cos}(\theta_1 - \theta_2)\right]$$

$$R_{1+}(\theta_1) = \frac{\eta N}{2}$$

The strong Bell Inequality is

$$\frac{R_{++}(\theta_1,\theta_2) - R_{++}(\theta_1,\theta_2') + R_{++}(\theta_1',\theta_2) + R_{++}(\theta_1',\theta_2')}{R\ (\theta'\ ) + R\ (\theta\ )} \leq$$

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Taking

$$\theta_1 = 45°,\ \ \theta_1' = 135°,\ \ \theta_2 = 270°,\ \ \theta_2' = 0°$$

The LHS is

$$1.207\ \eta g$$

In order for the quantum mechanical predictions to violate the inequality, we must have

$$\eta g \geq \frac{1}{1.207} = 0.828$$

We expect

$$\eta \geq 0.98,\ \ g \approx 0.97$$

$$\eta g \geq 0.95$$

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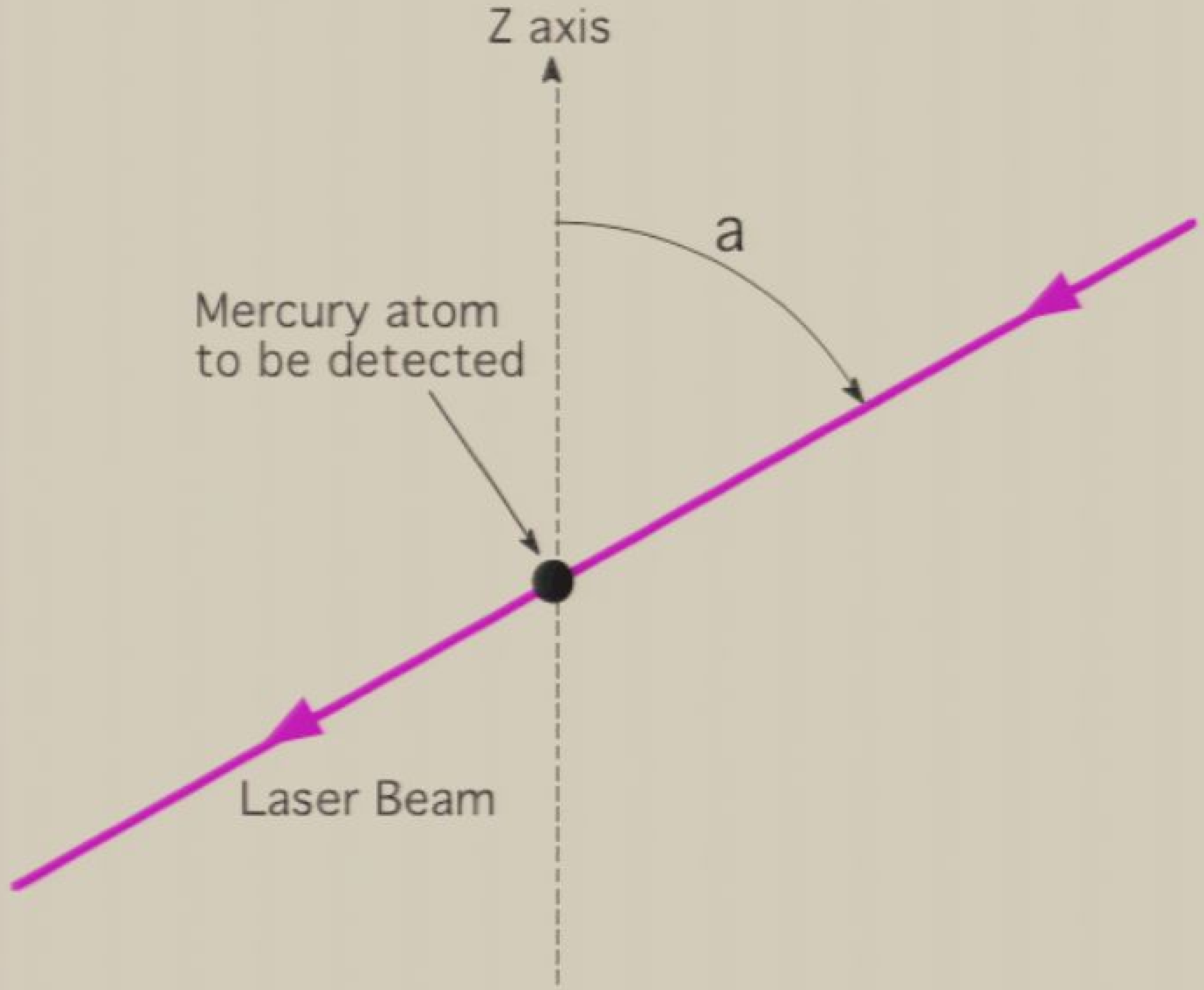
Enforcing locality



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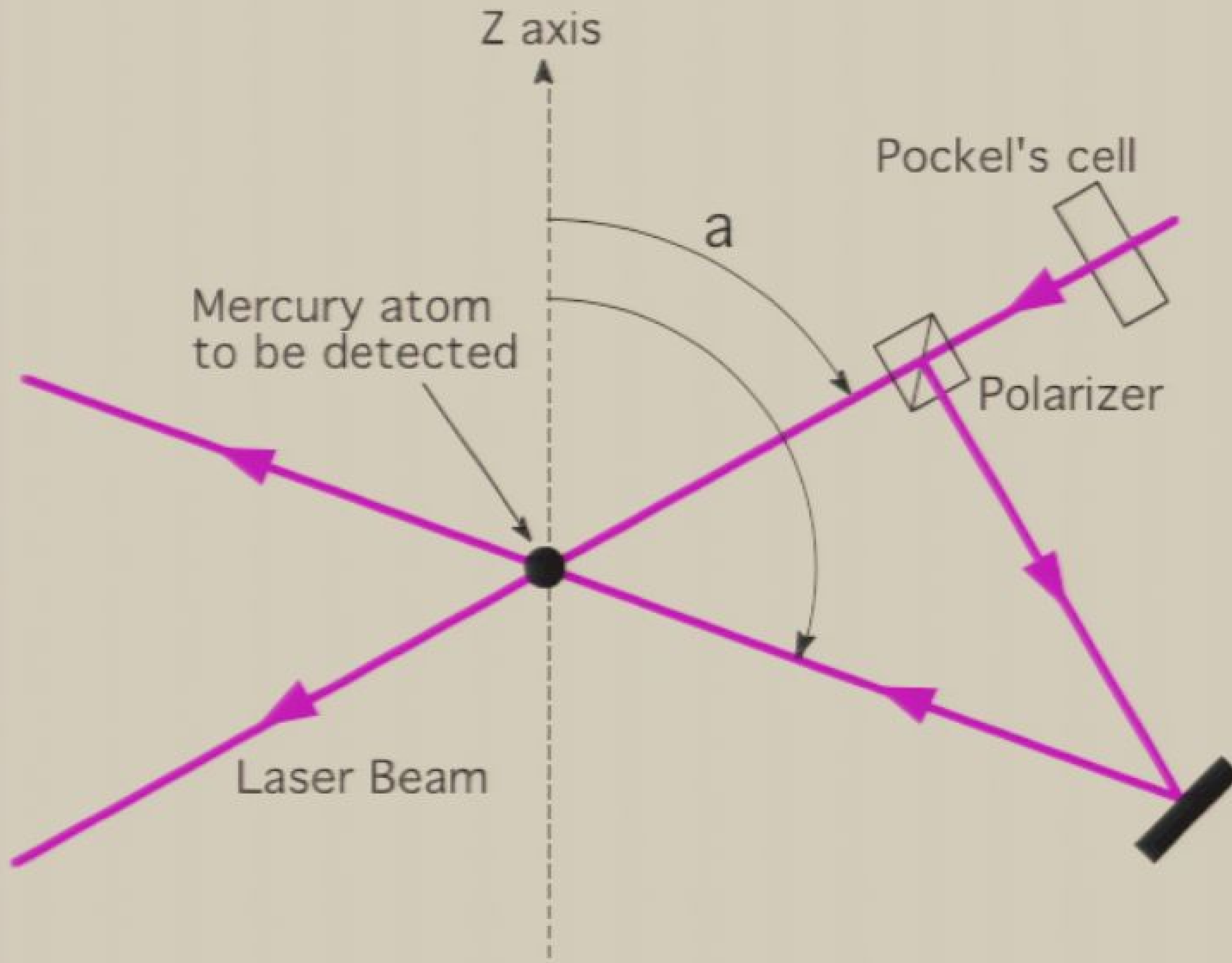
Enforcing locality



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THE END

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