Texas A&M Physics & Astronomy

Seven Pines Symposium XVII 2013

Bell Inequality Experiments

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Bell:

Hidden variables:

Restore causality and locality to quantum mechanics.

Locality:

The result of a measurement on one system is unaffected by operations on a distant system with which it has interacted in the past.

von Neumann

Proved in 1932 that a hidden variable interpretation of QM was not possible. His argument held sway until Bell showed the it was circular.

David Mermin: von Neumann's argument was silly!!

Reviews of Modern Physics <u>65</u>, 803-815 (1993).

Louisa Gilder "The Age of Entanglement"

"Clauser was trying to get a job. 'I must have applied to at least a dozen different places, and at all of them I was totally rejected.' Universities were uneasy about hiring a professor who would encourage the next generation to question the foundations of quantum theory."

"Fry himself had better luck with academia." Realizing that the tenure committee was about to reject the Bell experimenter, one of Fry's friends asked Pipkin (Holt's advisor at Harvard) to come to College Station, TX." . . . Pipkin's renown in atomic Physics won over the skeptical committee." Fry got tenure!

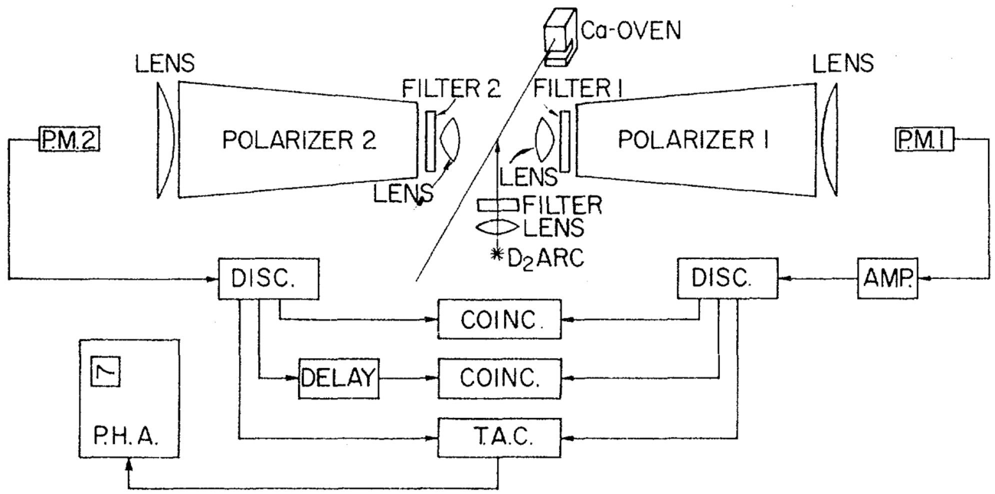
After Aspect visited with John Bell and completed a presentation on his planned experiment, ". . . Bell asked his first question with a trace of irony: 'Have you a permanent position?' "

"Aspect was only a graduate student, but -- because of the Uniqueness of the French system, and in drastic contrast to his counterparts in America -- his position at the École Normale Supérieure was actually permanent. Even with this advantage, it was not easy."

There will be serious fights," Bell warned him.

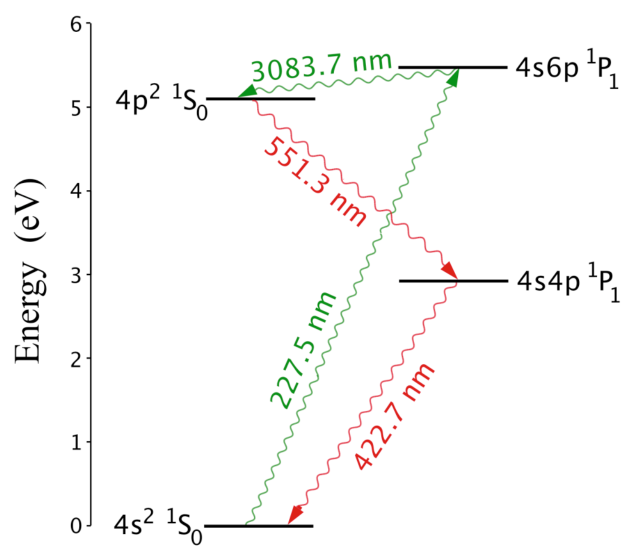
(1972) Experimental Test of Local Hidden-Variable Theories

Stuart J. Freedman and John F. Clauser



Beam of Ca atoms excited to $4s6p\,^1P_1$ state by D_2 arc lamp.

≈7% decay to the initial state of cascade, $4p^2\,^1S_0$.



Pile of plates polarizers

λ=551.3 nm, 422.7 nm

$$\delta = \left| \frac{R(67.5^\circ)}{R_0} - \frac{R(22.5^\circ)}{R_0} \right| \leq \frac{1}{4}$$

$$\delta = 0.300 \pm 0.008$$

$$\delta_{QM} = 0.301$$

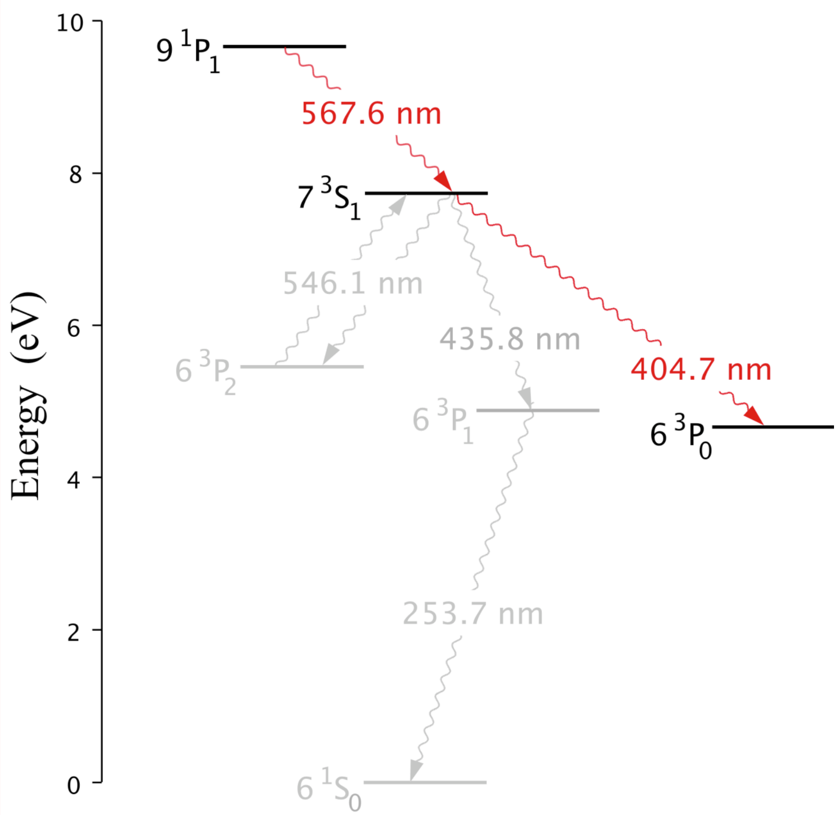
200 hours

(1973) Atomic Cascade Experiments
Ph.D. Thesis, Harvard University

Richard A. Holt (advisor: Frank Pipkin)

Zero nuclear spin isotope ^{198}Hg

Pumped into 9^1P_1 state by 100 eV electron beam



Calcite polarizers

λ=567.6 nm, 404.7 nm

$$\delta = \left| \frac{R(67.5^\circ)}{R_0} - \frac{R(22.5^\circ)}{R_0} \right| \leq \frac{1}{4}$$

$\delta = 0.216 \pm 0.013$

$\delta_{QM} = 0.266$

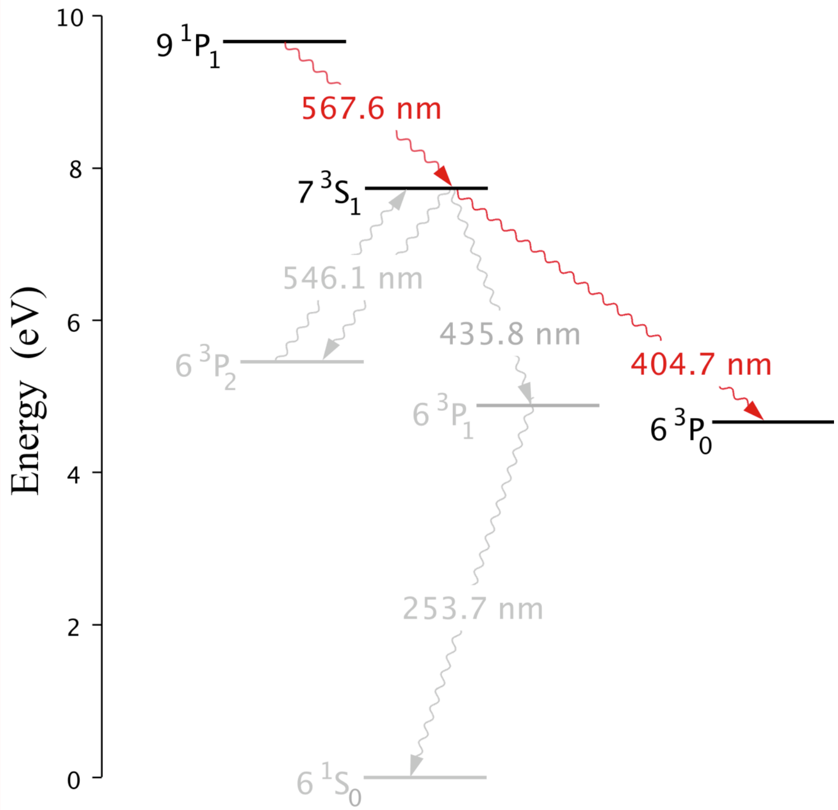
(1976) Experimental Investigation of a Polarization Correlation Anomaly

John F. Clauser

Repeat version of Holt experiment

91% zero nuclear spin isotope ^{202}Hg; 2.1% ^{199}Hg; 2.2% ^{201}Hg

Pumped into 9^1P_1 state by 135 eV electron beam



Pile of plates polarizers

λ=567.6 nm, 404.7 nm

$$\delta=\left|\frac{R(67.5^\circ)}{R_0}-\frac{R(22.5^\circ)}{R_0}\right|\leq\frac{1}{4}$$

$$\delta=0.2885\pm0.0093$$

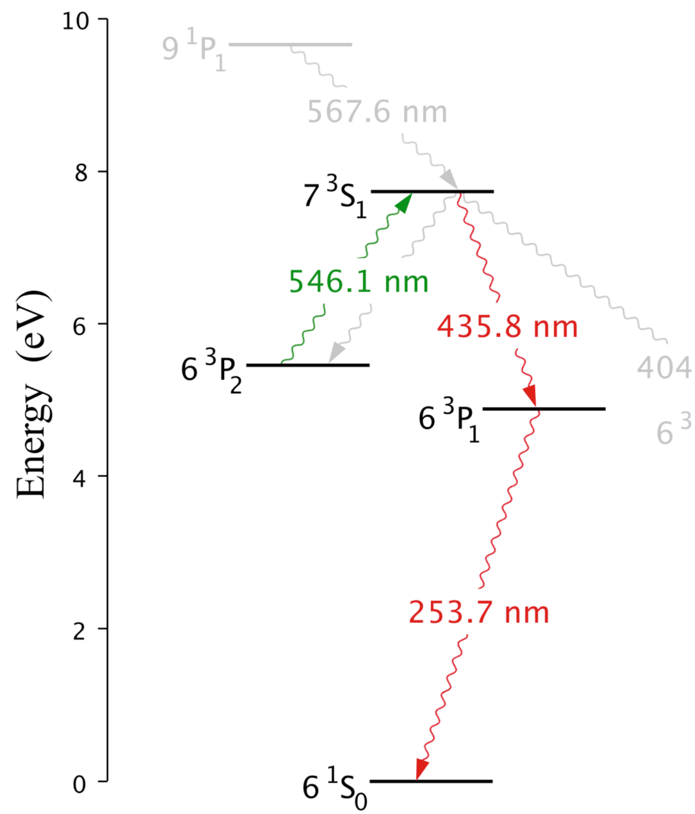
$$\delta_{QM}=0.2848$$

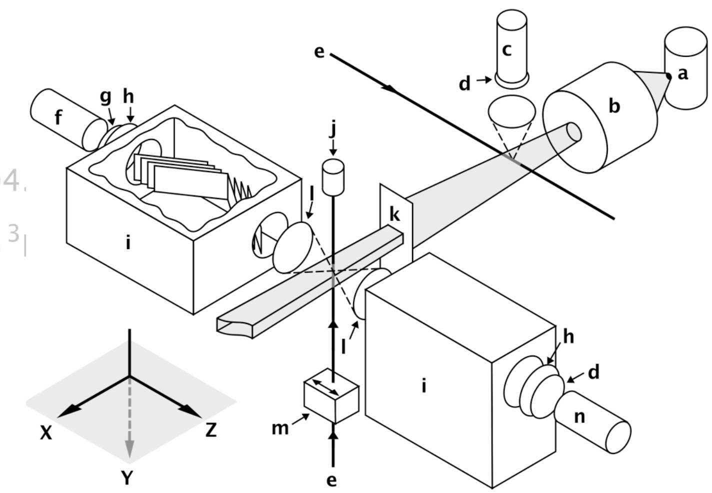
412 hours

(1976) Experimental Test of Local Hidden-Variable Theories

Edward S. Fry and Randall C. Thompson

Pump Hg atoms in an atomic beam into the metastable 6 $^3P_2$ state. Down stream a 546.1 nm dye laser excites only ^{200}Hg atoms to the 7 $^3S_1$ initial state of the cascade.





Pile of plates polarizers

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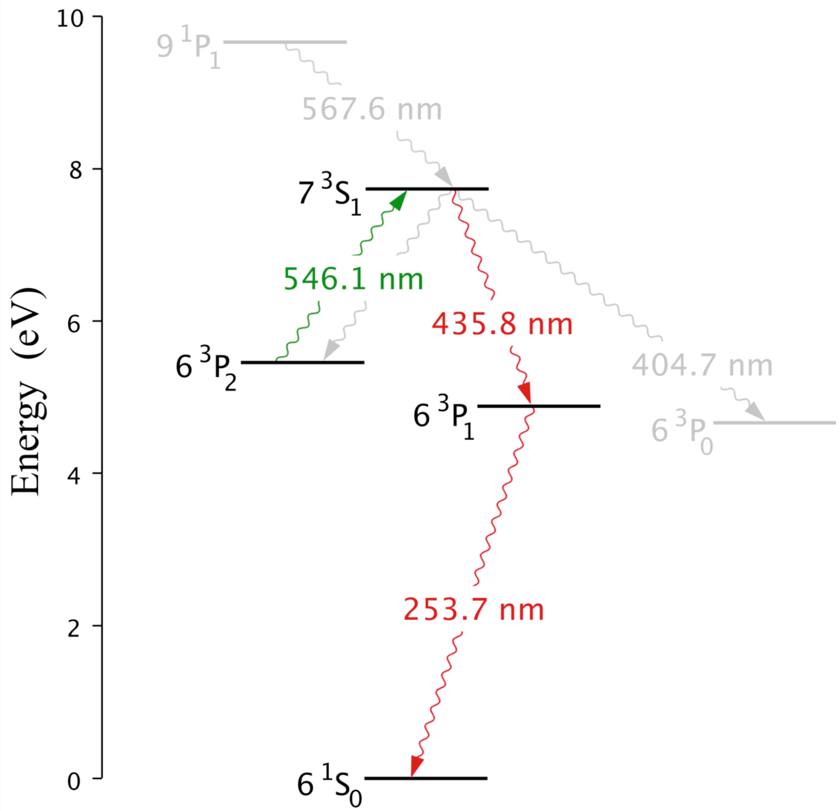
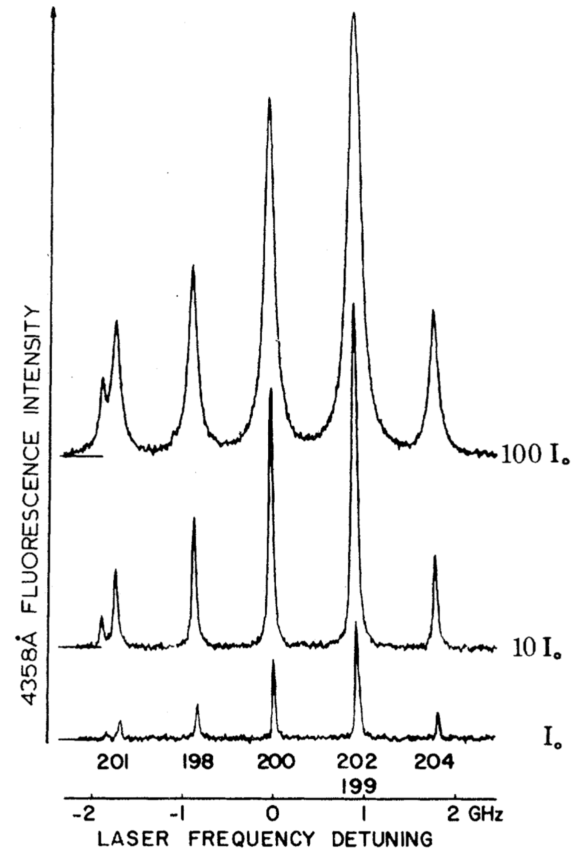
A 546.1 nm dye laser excites <u>only</u> ^{200}Hg atoms to the 7 $^3S_1$ initial state of the cascade.





Pile of plates polarizers

λ=435.8 nm, 253.7 nm

$$\delta=\left|\frac{R(67.5^\circ)}{R_0}-\frac{R(22.5^\circ)}{R_0}\right|\leq\frac{1}{4}$$

$\delta=0.296\pm0.014$

$\delta_{QM}=0.294\pm0.007$

80 minutes

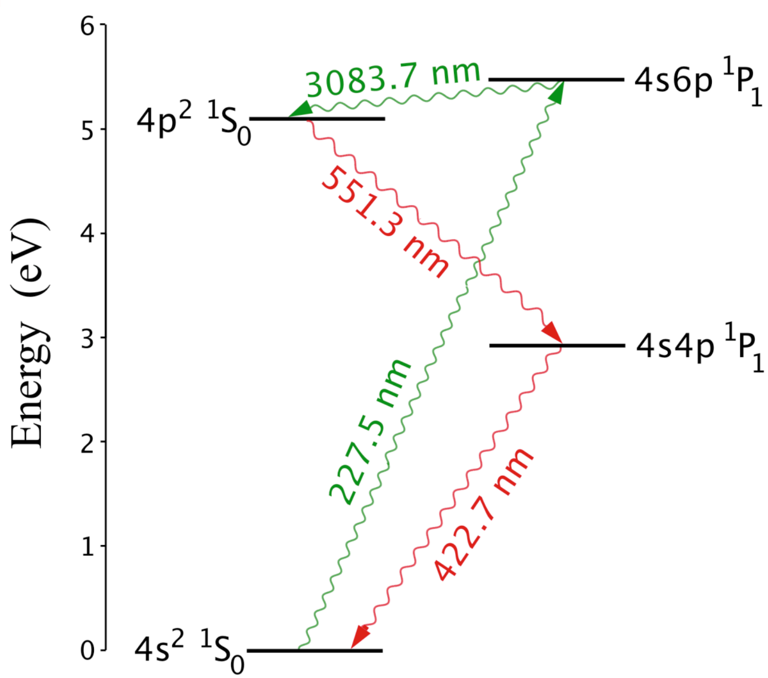
(1981) Experimental Tests of Realistic Local Theories via Bell's Theorem

Alain Aspect, Philippe Grangier, and Gérard Roger

Initial state of Ca atoms in an atomic beam are pumped by two photon process:

406.7 nm from a single-mode Krypton ion laser

581 nm from a single-mode Rhodamine 6G dye laser



Pile of plates polarizers

$\lambda = 551.3$ nm, 422.7 nm

$$\delta = \left| \frac{R(67.5^\circ)}{R_0} - \frac{R(22.5^\circ)}{R_0} \right| \leq \frac{1}{4}$$

$$\delta = 0.3072 \pm 0.0043$$

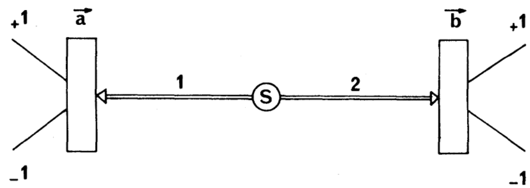
$$\delta_{QM} = 0.308 \pm 0.002$$

150 concidences/s

(1982) Realization of EPR-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

Alain Aspect, Philippe Grangier, and Gérard Roger

Cascade photon source as before except two channel polarizers instead of a pile of plates.

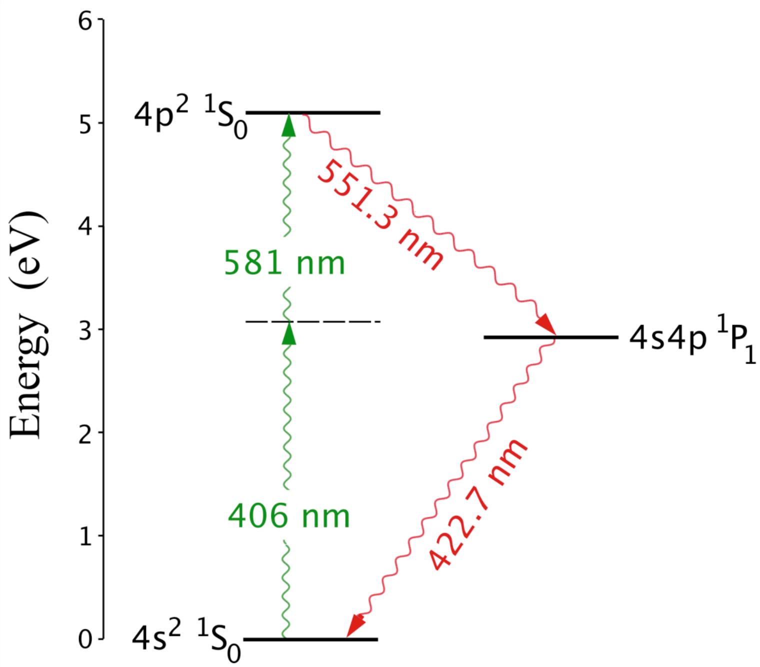


$$E(\vec{a},\vec{b})=\frac{R_{++}(\vec{a},\vec{b})+R_{--}(\vec{a},\vec{b})-R_{+-}(\vec{a},\vec{b})-R_{-+}(\vec{a},\vec{b})}{R_{++}(\vec{a},\vec{b})+R_{--}(\vec{a},\vec{b})+R_{+-}(\vec{a},\vec{b})+R_{-+}(\vec{a},\vec{b})}$$

$$S=E(\vec{a},\vec{b})-E(\vec{a},\vec{b}')+E(\vec{a}',\vec{b})+E(\vec{a}',\vec{b}')$$

$$-2 \le S \le 2$$

Maximum violation at $S = 3E(22.5^\circ)-E(67.5^\circ)$



$S_{expt} = 2.697 \pm 0.015$

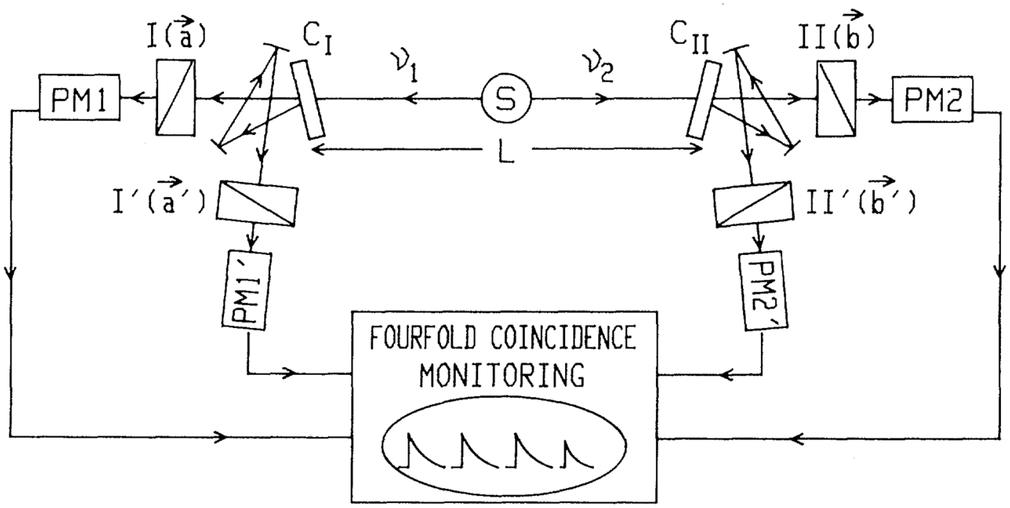
$S_{QM} = 2.70 \pm 0.05$

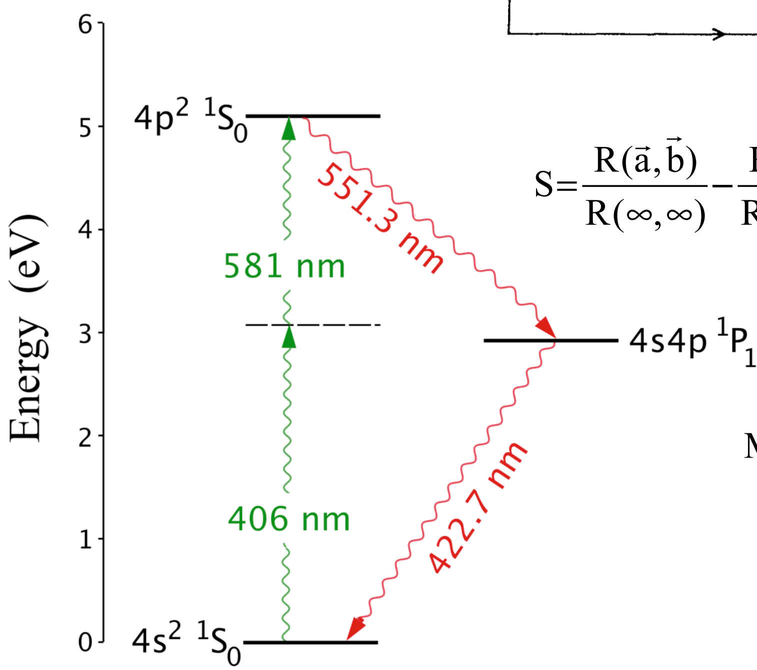
(1982) Experimental Test of Bell's Inequalities Using Time-Varying Analyzers

Alain Aspect, Jean Dalibard, and Gérard Roger

Cascade photon source as before.

Two polarizers in each arm with a fast switch between them.





$$S=\frac{R(\vec a,\vec b)}{R(\infty,\infty)}-\frac{R(\vec a,\vec b')}{R(\infty,\infty')}+\frac{R(\vec a',\vec b)}{R(\infty',\infty)}+\frac{R(\vec a',\vec b')}{R(\infty',\infty')}-\frac{R(\vec a',\infty)}{R(\infty',\infty)}-\frac{R(\infty,\vec b)}{R(\infty,\infty)}$$

$$-1 \le S \le 0$$

Maximum violation at $(\vec a,\vec b)=(\vec a',\vec b)=(\vec a',\vec b')=22.5^\circ$ and $(\vec a,\vec b')=67.5^\circ$

$$S_{expt}=0.101\pm0.02$$

$$S_{QM}=0.112$$

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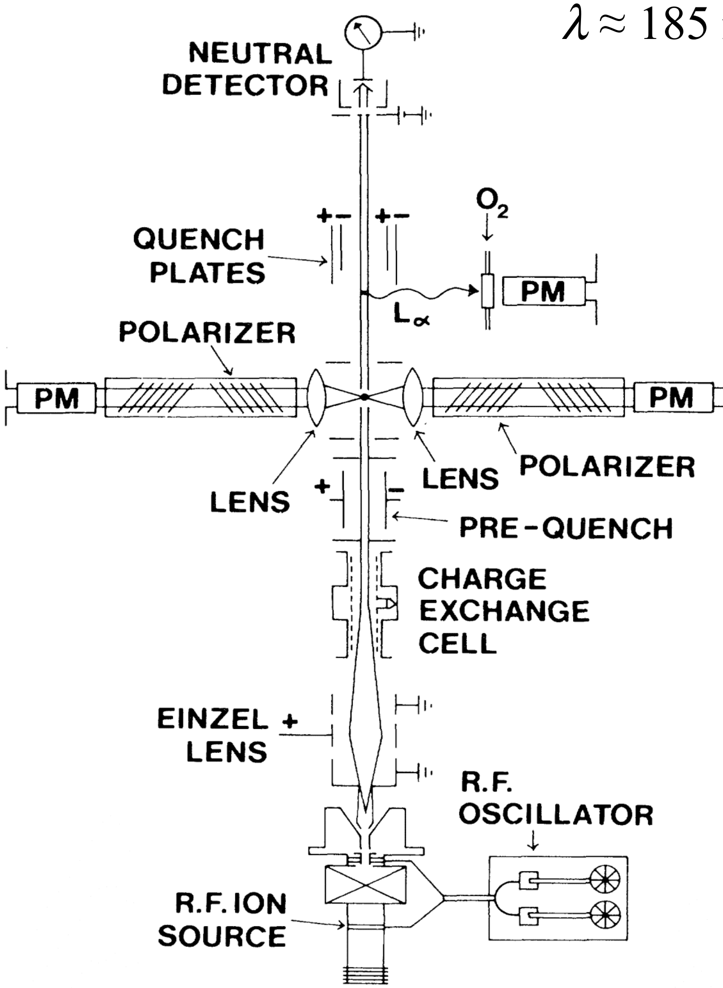
(1985) Polarization Correlation of the Two Photons Emitted by Metastable Atomic Deuterium: A Test of Bell's Inequality

W. Perrie, A. J. Duncan, H. J. Beyer, and H. Kleinpoppen

Two photons emitted simultaneously via decay of metastable deuterium atoms, $\lambda \approx 185$ nm to 355 nm



Pile of plates polarizers

λ=185 nm to 355 nm

$$\delta=\left|\frac{R(67.5^\circ)}{R_0}-\frac{R(22.5^\circ)}{R_0}\right|\leq\frac{1}{4}$$

$\delta=0.268\pm0.01$

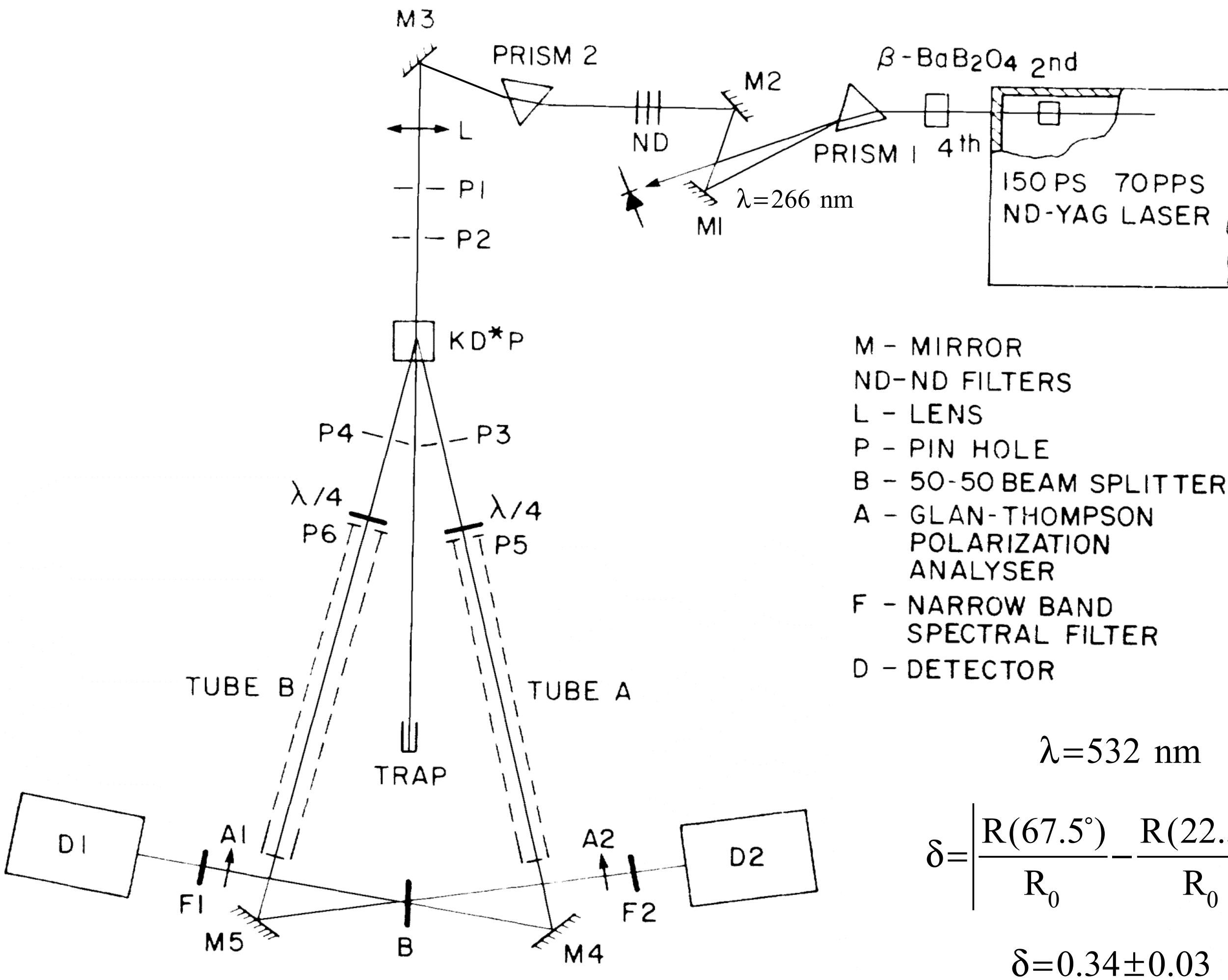
$\delta_{QM}=0.272\pm0.008$

0.14 concidences/s

(1988) EPR Experiment Using Pairs of Light Quanta Produced by Optical Parametric Down Conversion

Y. H. Shih and C. O. Alley

Type-I phase matching: produces parallel polarized down-converted photons



λ=532 nm

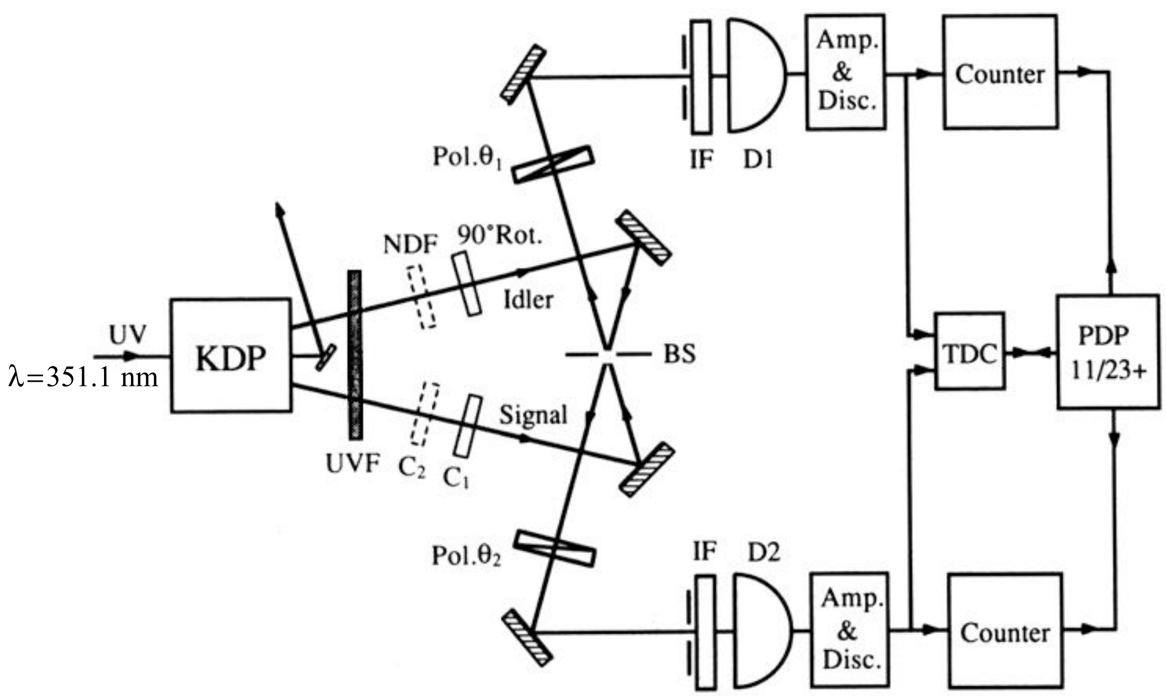
$$\delta = \left| \frac{R(67.5^\circ)}{R_0} - \frac{R(22.5^\circ)}{R_0} \right| \le \frac{1}{4}$$

$$\delta = 0.34 \pm 0.03$$

(1988) Violation of Bell's Inequality and Classical Probability in a Two-Photon Correlation

Z. Y. Ou and L. Mandel

Type-I phase matching



$$S = R(\theta_1,\theta_2) - R(\theta_1,\theta_2') + R(\theta_1',\theta_2) + R(\theta_1',\theta_2') - R(\theta_1',\infty) - R(\infty,\theta_2) \le 0$$

$\theta_1 = 22.5^\circ$ $\theta_1' = 67.5^\circ$ $\theta_2 = 45^\circ$ $\theta_2' = 0^\circ$

$S_{expt} = 11.5 \pm 2$

Y. H. Shih and C. O. Alley, Phys. Rev. Lett. 61, 2921 (December, 1988)

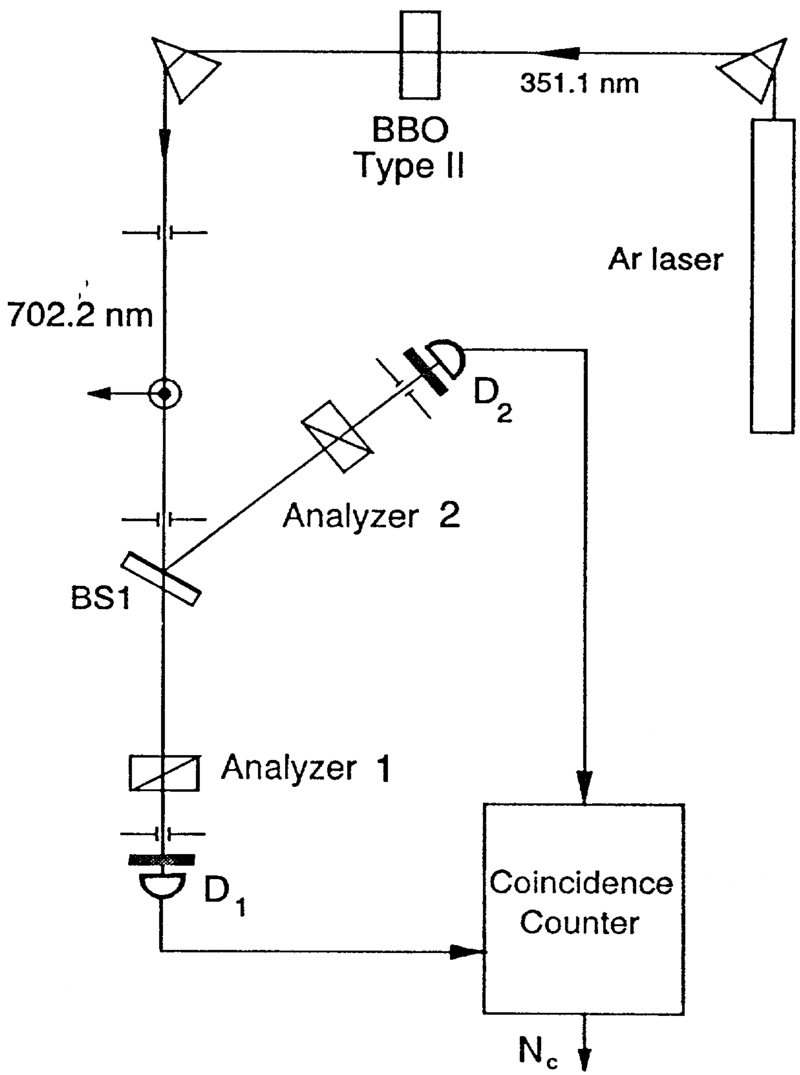
Z. Y. Ou and L. Mandel, Phys. Rev. Lett. 61, 50 (July, 1988)

C. O. Alley and Y. H. Shih, "***A new type of EPR experiment***" in Proceedings of the Second International Symposium on Foundations of Quantum Mechanics in the Light of New Technology, Tokyo, 1986, edited by M. Namiki et al. (Physical Society of Japan, Tokyo, 1987), pp. 47-52.

In the Ou and Mandel paper, they reference the Tokyo proceedings and state *". . . we report another photon correlation experiment of this type, similar to one first performed by Alley and Shih, in which the observed violation of Bell' s inequality for two separated particles is as large as 6 standard deviations."*

(1993) EPR-Bohm Experiment Using Pairs of Light Quanta Produced by Type-II Parametric Down-Conversion

T. E. Kiess, Y. H. Shih, A. V. Sergienko, and C. O. Alley



Type-II phase matching:
produces down-converted photons that are already perpendicular polarized

$\lambda = 702.2$ nm

$$\delta = \left| \frac{R(67.5^\circ)}{R_0} - \frac{R(22.5^\circ)}{R_0} \right| \leq \frac{1}{4}$$

$\delta = 0.316 \pm 0.003$

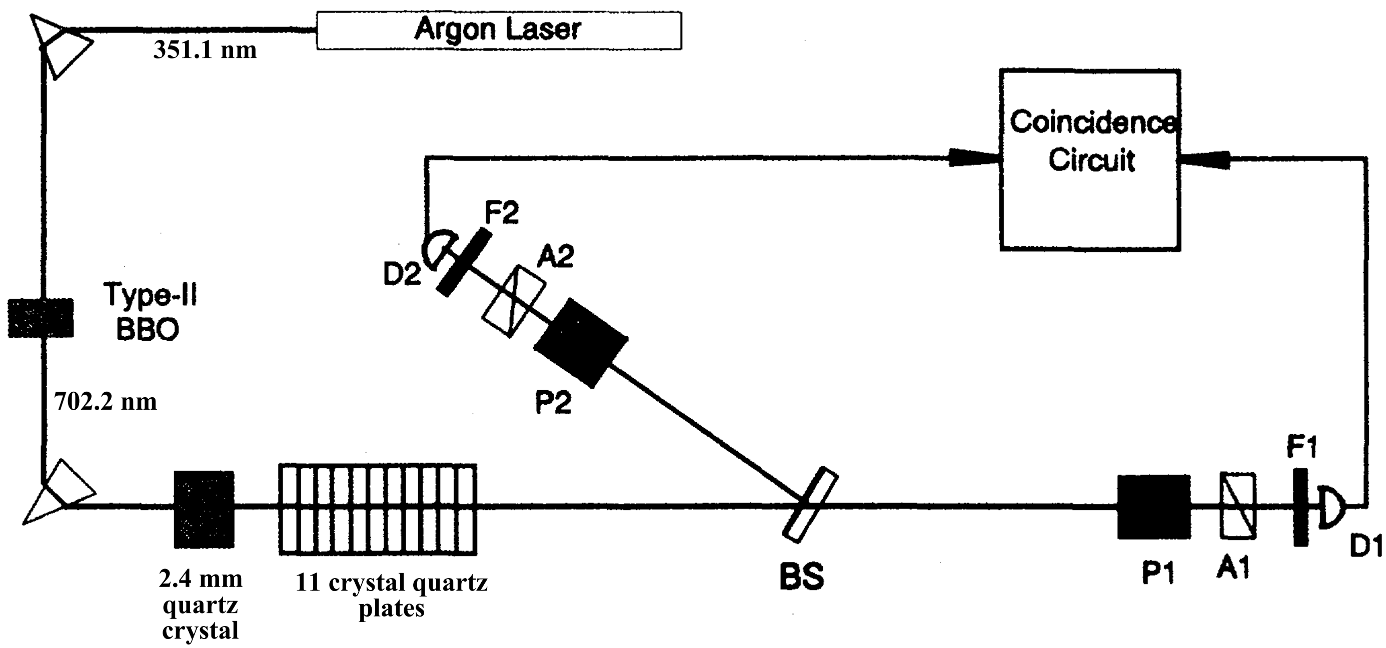
$\delta_{QM} = 0.354$

(1995) Experimental tests of Bell's inequalities based on space-time and spin variables

T. B. Pittman, Y. H. Shih, A. V. Sergienko, and M. H. Rubin

Type-II phase matching (perpendicular polarized photons)

Double entanglement: state is entangled in both spin and space-time variables.



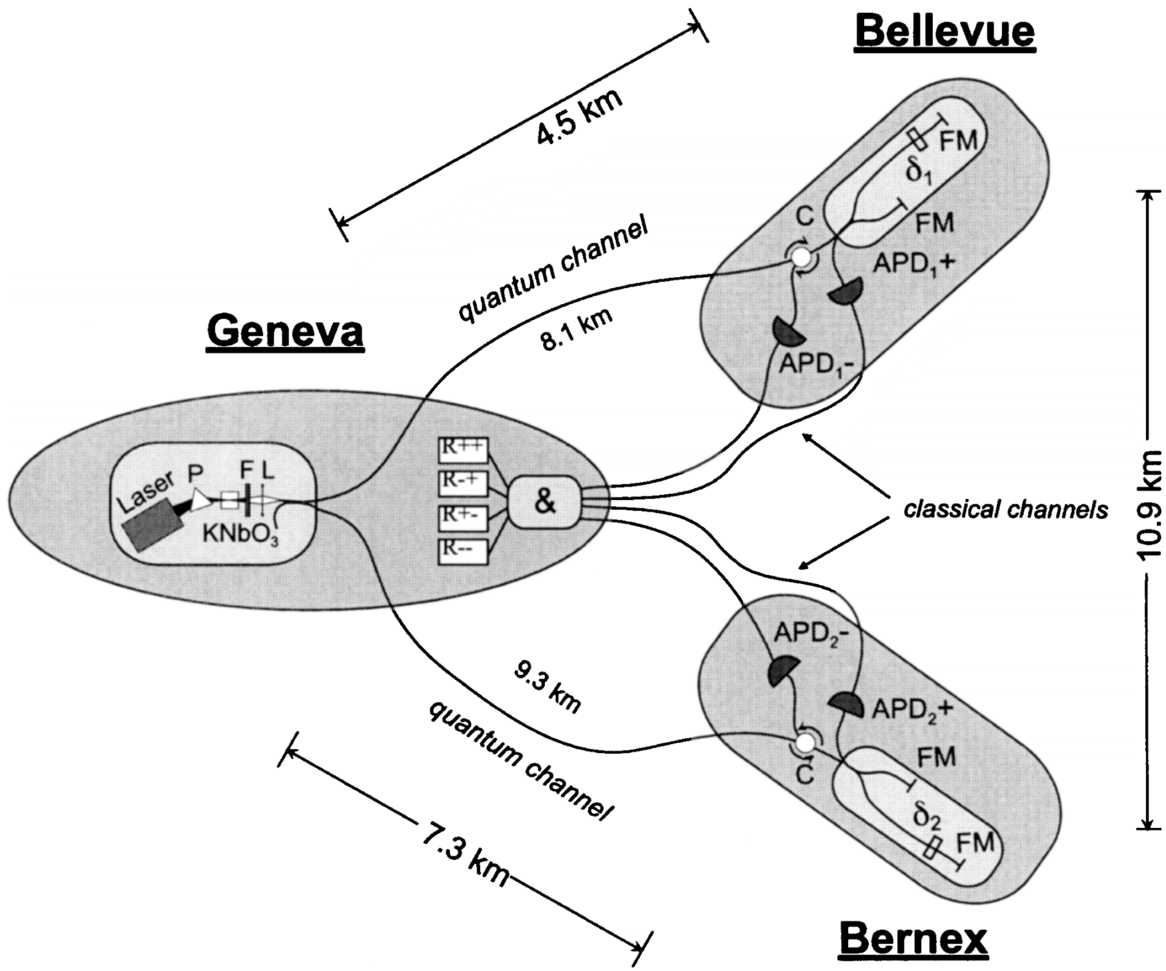
$$\delta=\left|\frac{R(67.5^{\circ})}{R_0}-\frac{R(22.5^{\circ})}{R_0}\right|\leq\frac{1}{4}$$

$$\delta=0.309\pm0.009$$

(1998) Violation of Bell Inequalities by Photons More Than 10 km Apart

W. Tittel, J. Brendel, H. Zbinden, and N. Gisin

Parametric down-conversion (type-I phase matching) of 655 nm light from a semiconductor laser, *i.e* photons have λ=1310 nm



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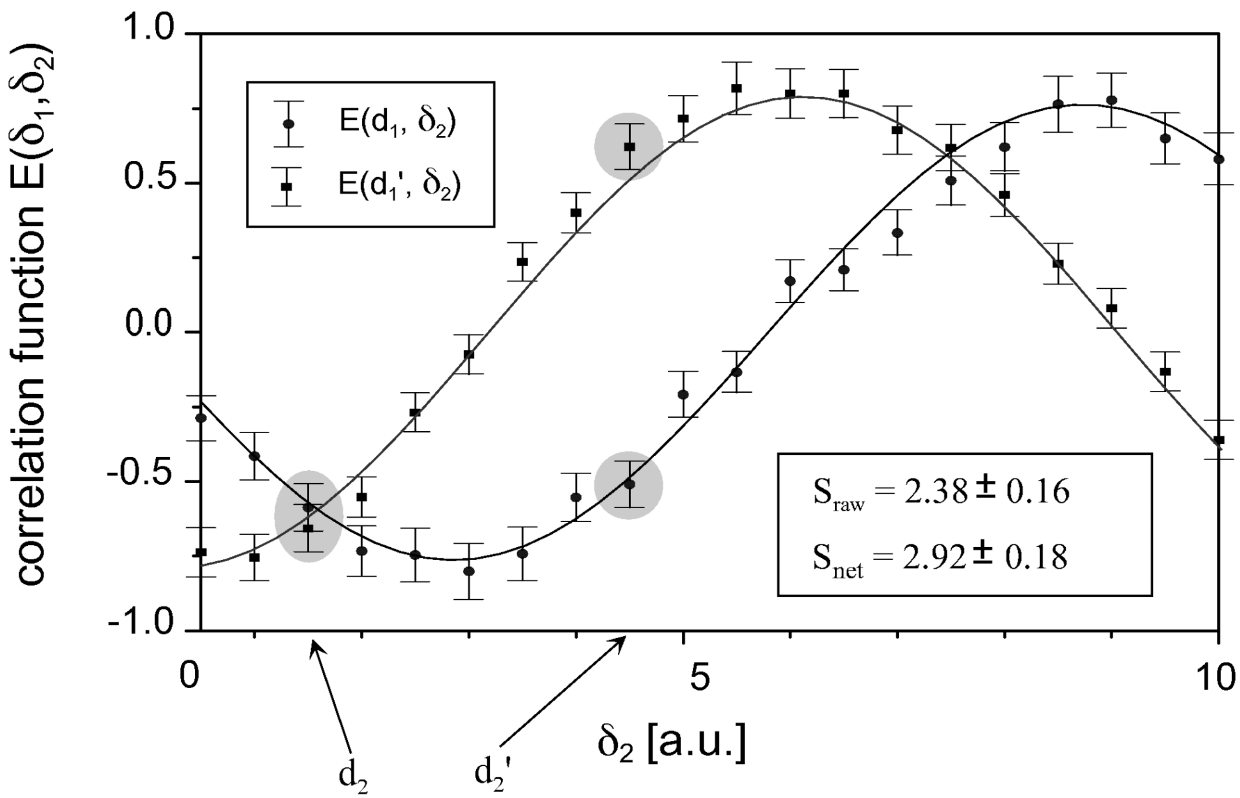
$$E(\delta_1,\delta_2)=\frac{R_{++}(\delta_1,\delta_2)+R_{--}(\delta_1,\delta_2)-R_{+-}(\delta_1,\delta_2)-R_{-+}(\delta_1,\delta_2)}{R_{++}(\delta_1,\delta_2)+R_{--}(\delta_1,\delta_2)+R_{+-}(\delta_1,\delta_2)+R_{-+}(\delta_1,\delta_2)}$$

$$S=\left|E(d_1,d_2)-E(d_1,d_2')+E(d_1',d_2)+E(d_1',d_2')\right|\leq 2$$



The correlation functions $E(d_1, \delta_2)$ and $E(d_1', \delta_2)$ are plotted as a function of phase δ_2.

(1998) Violation of Bell's inequality under strict Einstein locality conditions

Gregor Weihs, Thomas Jennewein, Christoph Simon,
Harald Weinfurter, and Anton Zeilinger

Type-II parametric down-conversion produces 702 nm photons.

Closed the locality loophole - used a quantum process to ensure the choice of detector was random. (More rigorous closure than Aspect, et al.)

$$S \leq 2$$

$$S_{QM} = 2\sqrt{2} = 2.83$$

$$S_{expt} = 2.73 \pm 0.02$$

(2001) Experimental violation of a Bell's inequality with efficient detection

M. A. Rowe, D. Kielpinski, V. Meyer, C. A. Sackett, W. M. Itano, C. Monroe & D. J. Wineland

Two massive entangled atoms:

Two $^9Be^+$ ions confined along the axis of a linear Paul trap (they are bosons).

First experiment to close the detection loophole

$$S \leq 2$$

$$S_{QM} = 2\sqrt{2} = 2.83$$

$$S_{expt} = 2.25 \pm 0.03$$

(2008) Bell Inequality Violation with Two Remote Atomic Qubits

D. N. Matsukevich, P. Maunz, D. L. Moehring, S. Olmschenk, and C. Monroe

Two massive entangled atoms:

- Two remote $^{171}Yb^{+}$ ions (bosons) separated by a distance of about 1 m
- Detection loophole closed

$$S \leq 2$$

$$S_{expt} = 2.22 \pm 0.07$$

(2009) Violation of Bell's inequality in Josephson phase qubits

Markus Ansmann, H. Wang, Radoslaw C. Bialczak, Max Hofheinz, Erik Lucero, M. Neeley, A. D. O'Connell, D. Sank, M. Weides, J. Wenner, A. N. Cleland & John M. Martinis

A pair of Josephson phase qubits serve as spin-1/2 particles that are entangled via an electromagnetic resonator

$$|S| \leq 2$$

$$S_{QM} = 2.064 \ \text{(reduced from the theoretical maximum of } 2\sqrt{2} \text{ by instrumental effects)}$$

$$S_{\exp t} = 2.0732 \pm 0.0003$$

(2013) Bell violation using entangled photons without the fair-sampling assumption

Marissa Giustina, Alexandra Mech, Sven Ramelow, Bernhard Wittmann, Johannes Kofler, Jörn Beyer, Adriana Lita, Brice Calkins, Thomas Gerrits, SaeWoo Nam, Rupert Ursin & Anton Zeilinger

Type-II phase matching (perpendicular polarized photons) produced 810 nm photons

98% photon detection efficiency

Tested Eberhard's Bell inequality that inherently does not rely on the fair-sampling assumption.

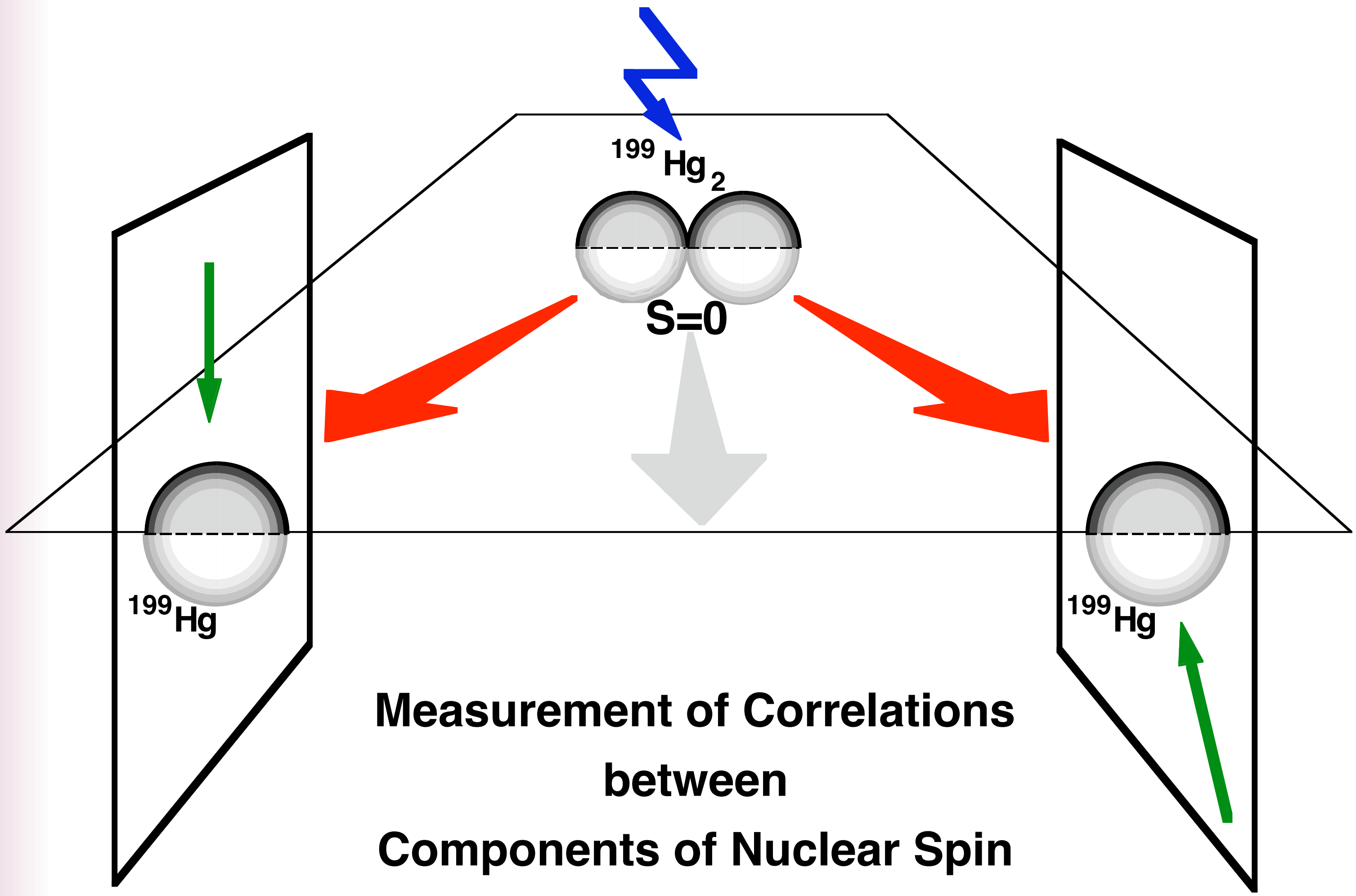
Experimentally violated Eberhard's Bell inequality by 70 standard deviations.

(2013) High-temperature high-pressure all-metal pulsed source of van der Waals dimers: Towards the Einstein-Podolsky-Rosen experiment

T. Urbanczyk and J. Koperski

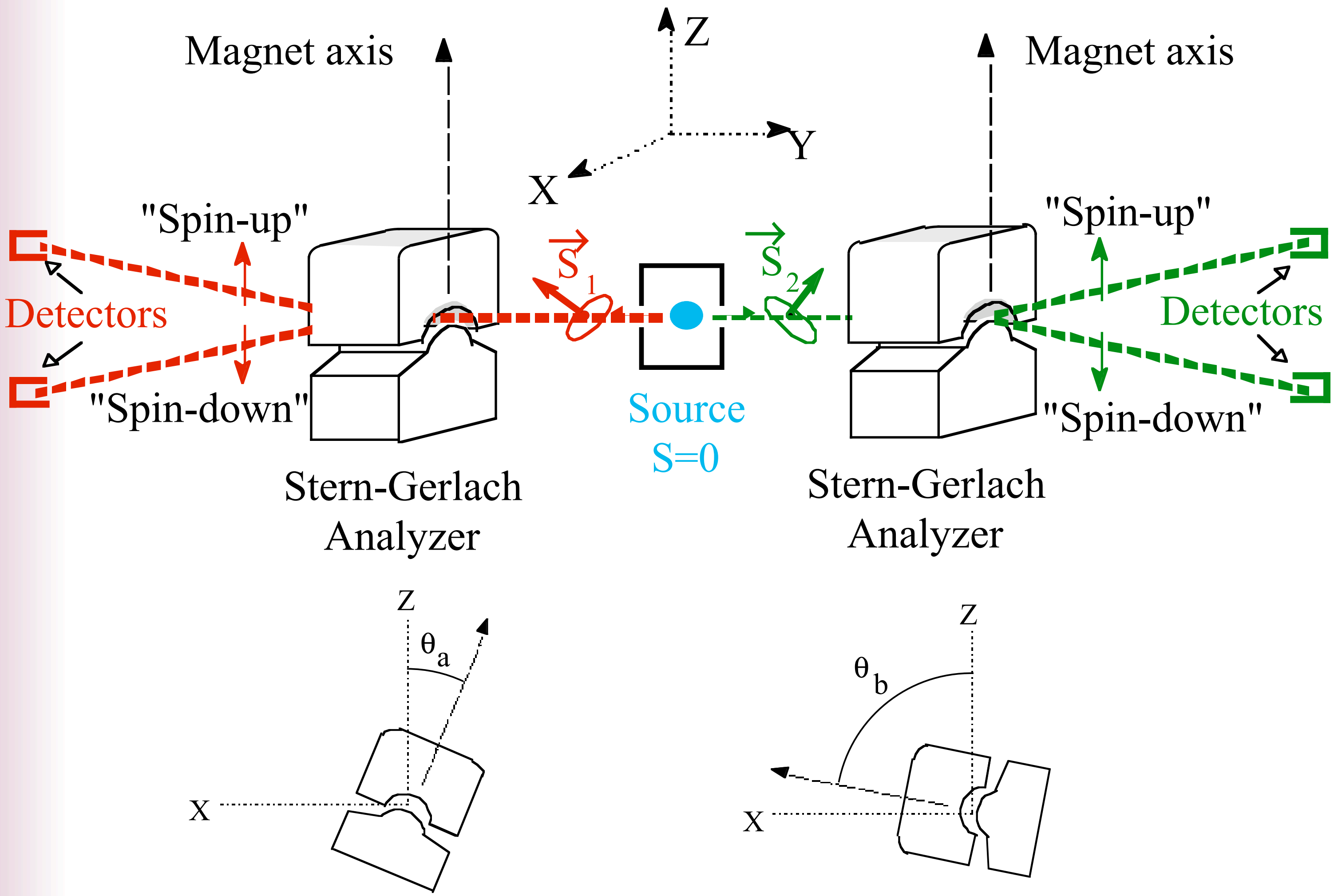
An experimental set-up dedicated to the realization of Bohm's spin-1/2 particle version of the Einstein-Podolsky-Rosen experiment for $^{111}Cd_2$ molecules

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



Measurement of Correlations between Components of Nuclear Spin

Bohm's version of EPR

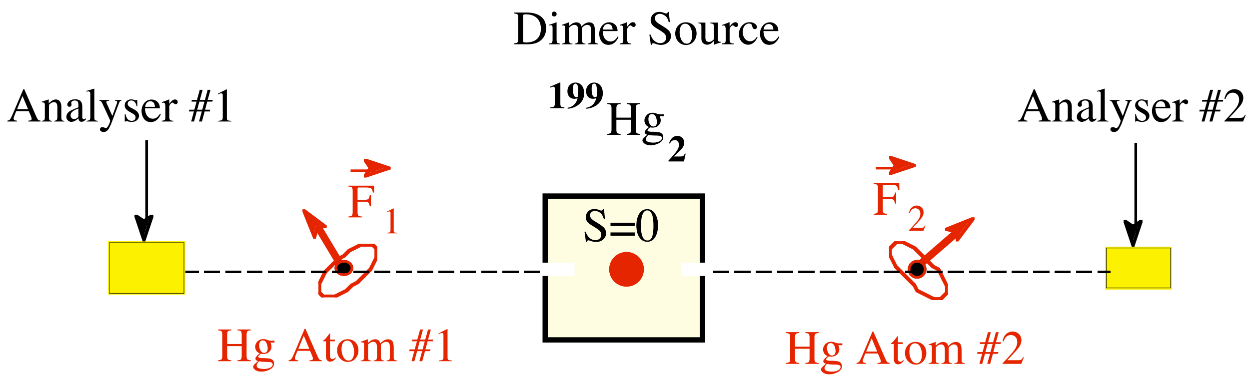


$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left\{|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2\right\}$$

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.



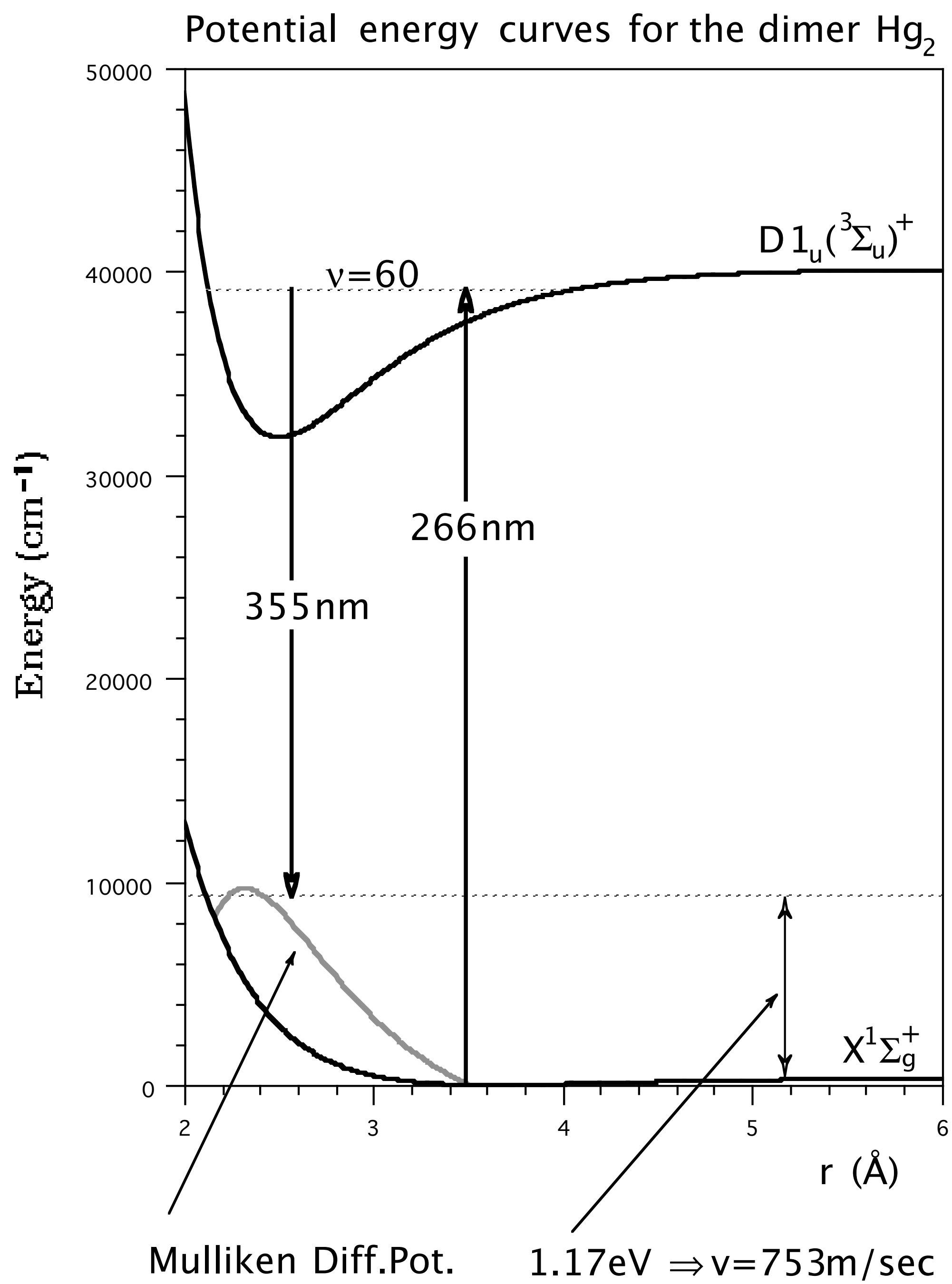
$J=0$ $\quad I = \frac{1}{2}$ $\quad F = I + J = \frac{1}{2}$

Analyzers determine component of F in a specific direction.

Measure correlations between different components of F.

DIMER

DISSOCIATION


Potential energy curves for the dimer Hg_2
50000
40000
30000
20000
10000
0
Energy (cm^{-1})
$D\,1_u(^3\Sigma_u)^+$
$\nu=60$
266nm
355nm
$X^1\Sigma_g^+$
2
3
4
5
6
r (Å)
Mulliken Diff.Pot.
1.17eV ⇒ v=753m/sec

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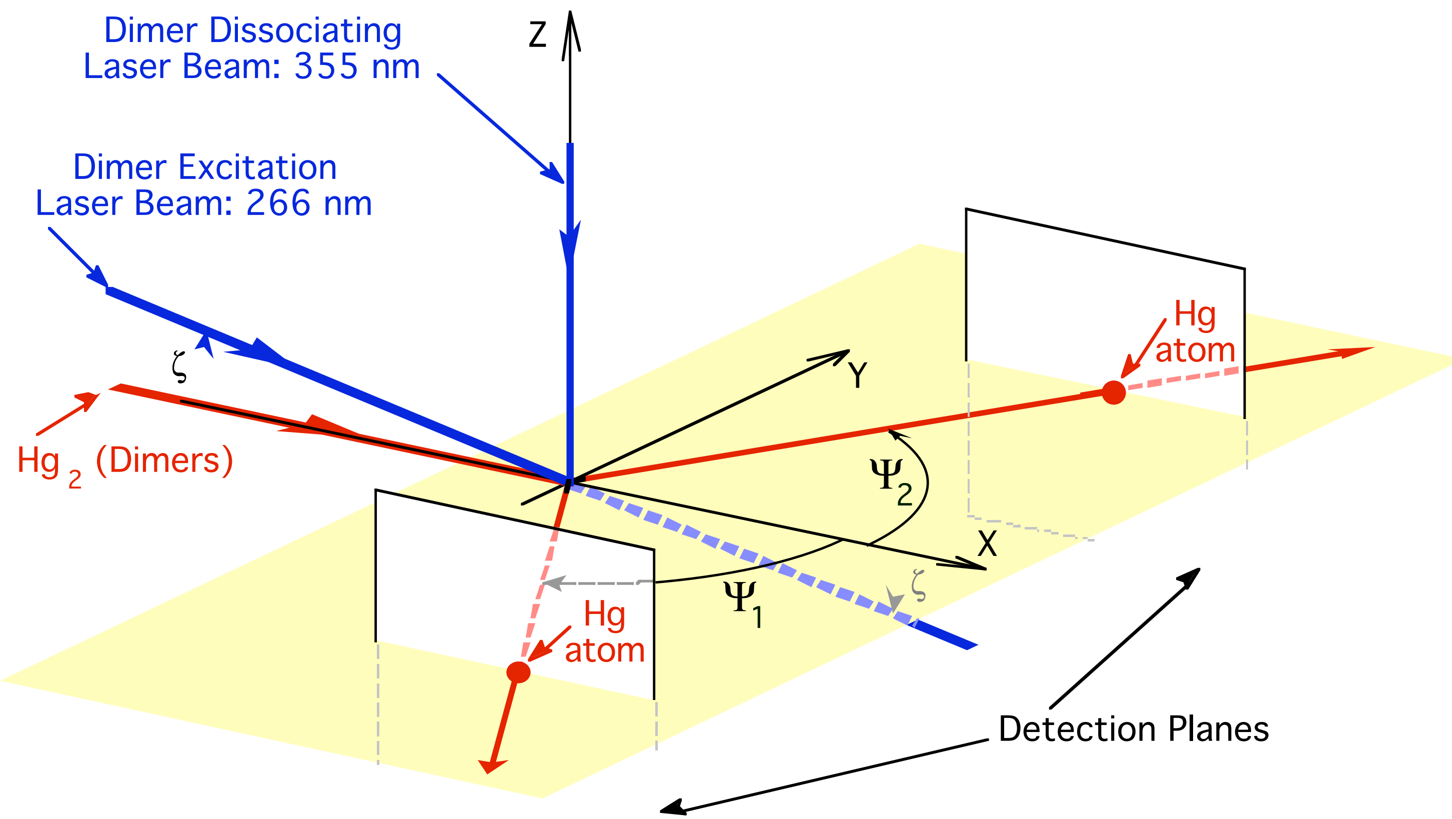

MERCURY ATOM

EXCITATION

and

IONIZATION

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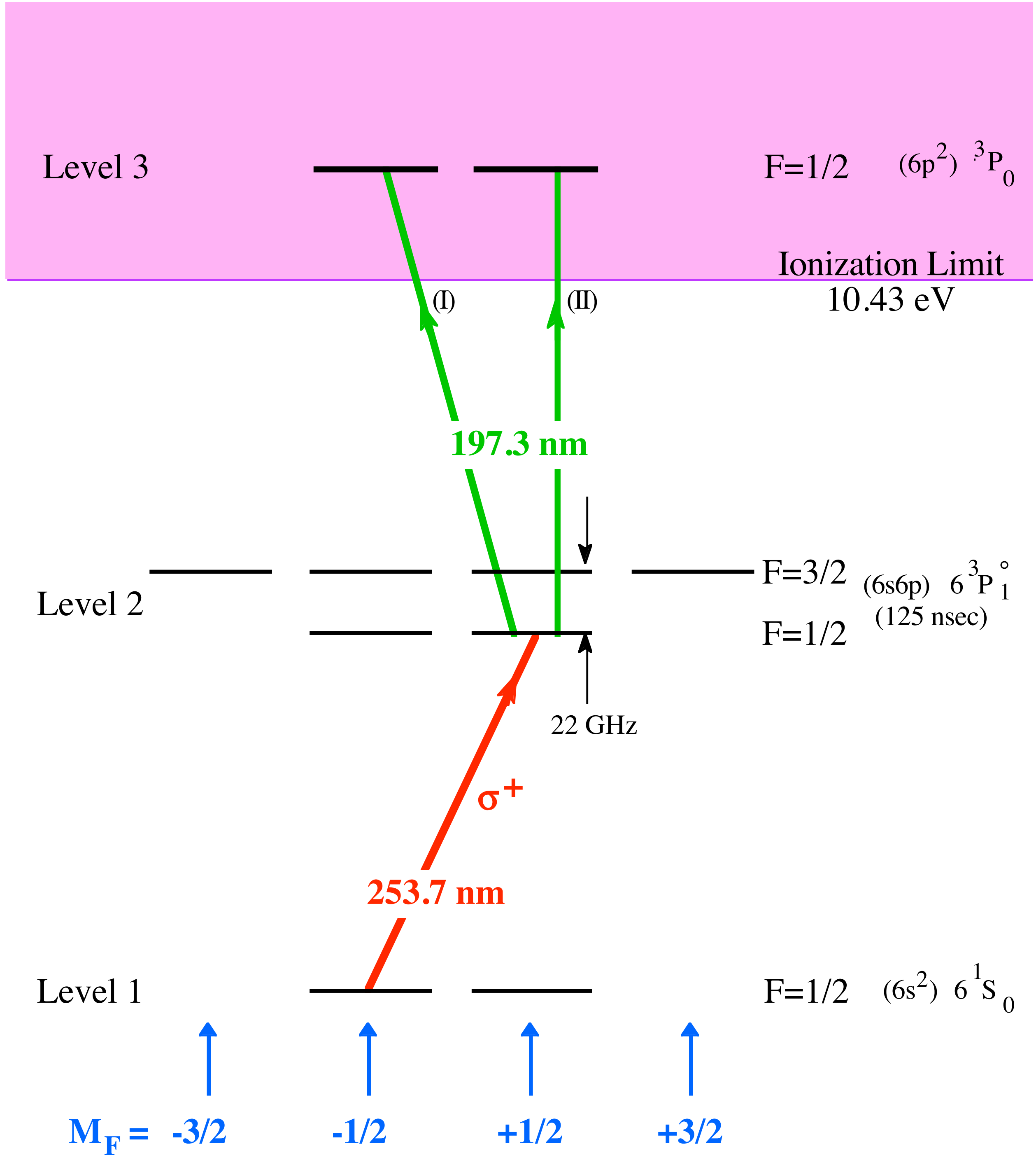

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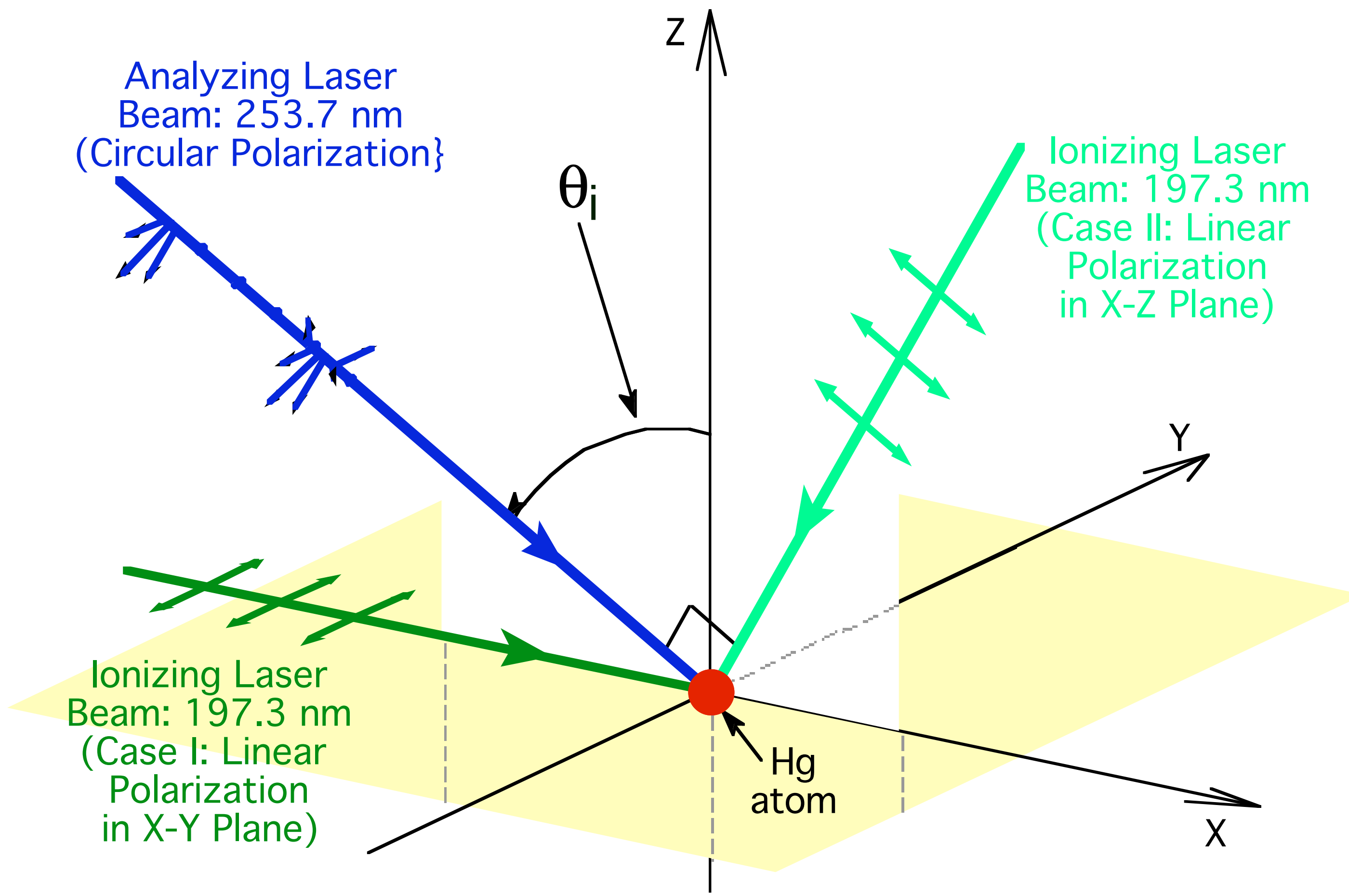

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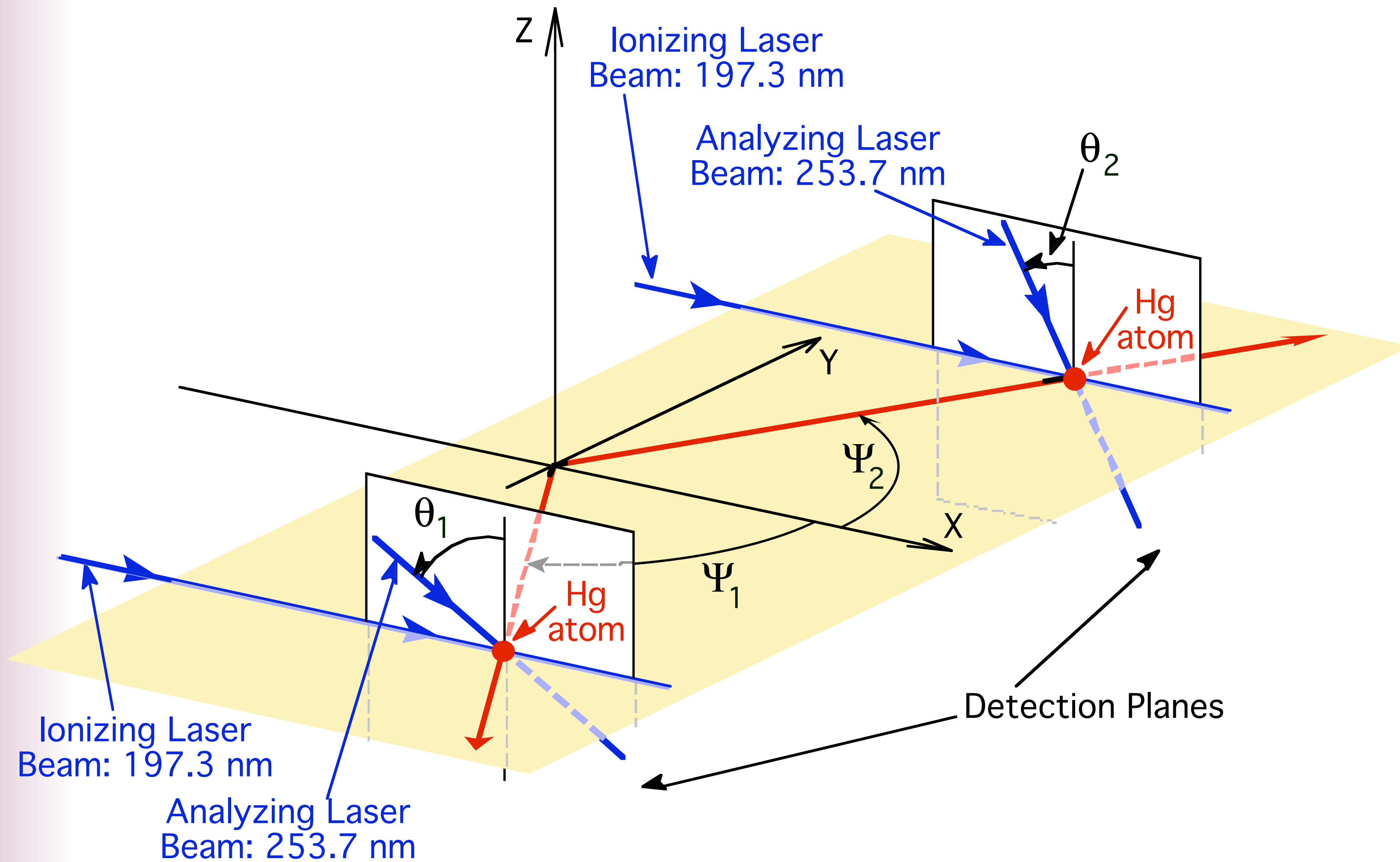

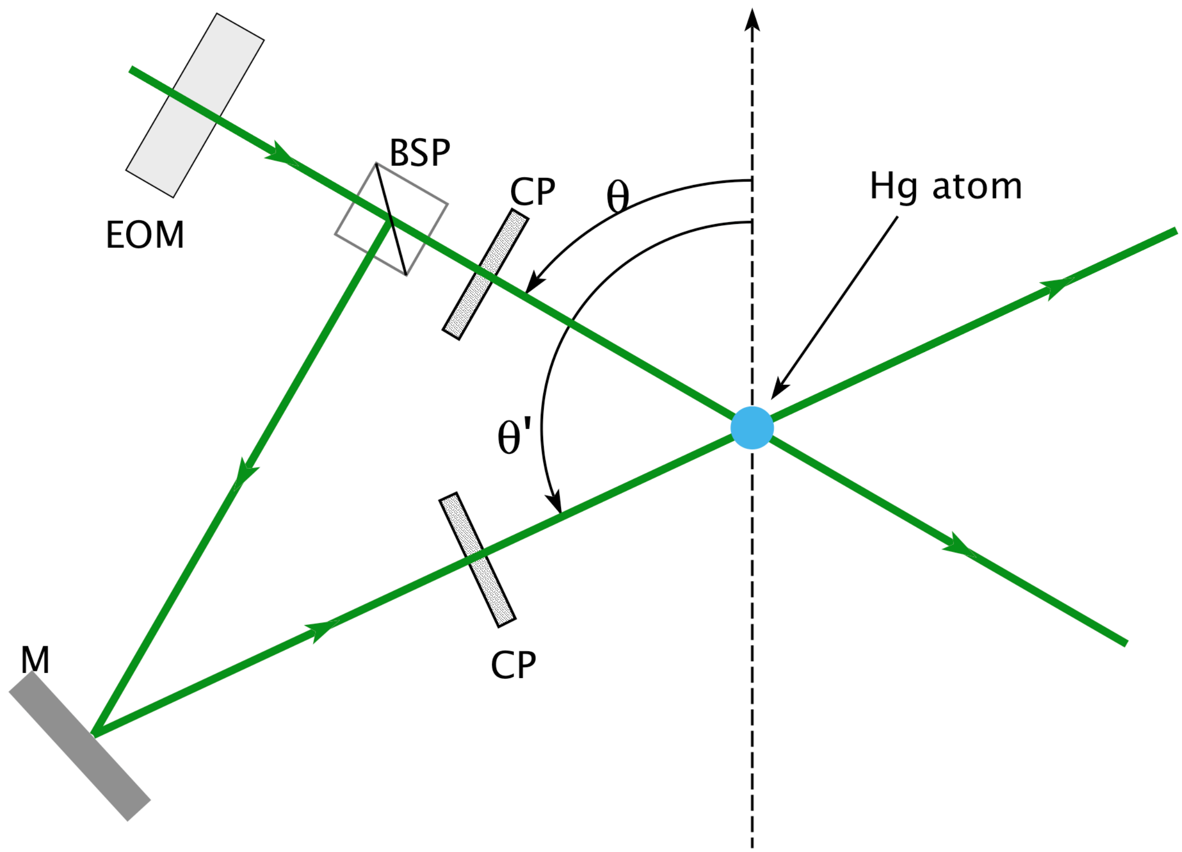

System for rapid switching of the direction of observation of the nuclear spin components.

Features

1) Efficient detectors
2) Enforce Einstein locality
3) Spin one-half fermions rather than bosons
4) Massive particles rather than massless photons.
5) Well inside the light cone rather than on it.
6) Entangled state exists for milliseconds vs. nanoseconds in photon experiments - a different time scale by **six orders of magnitude!**
7) Possible storage of the two components of the entangled state in frozen neon matrices

THE END