Texas A&M Physics & Astronomy

Saturday Morning Physics 2 26 11

Determinism
Einstein
and
Quantum Mechanics

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End of the 19th Century

Classical Physics:

classical mechanics (Newton)

classical electrodynamics (Maxwell)

Provides a firm and final foundation for all science, only the details were left.

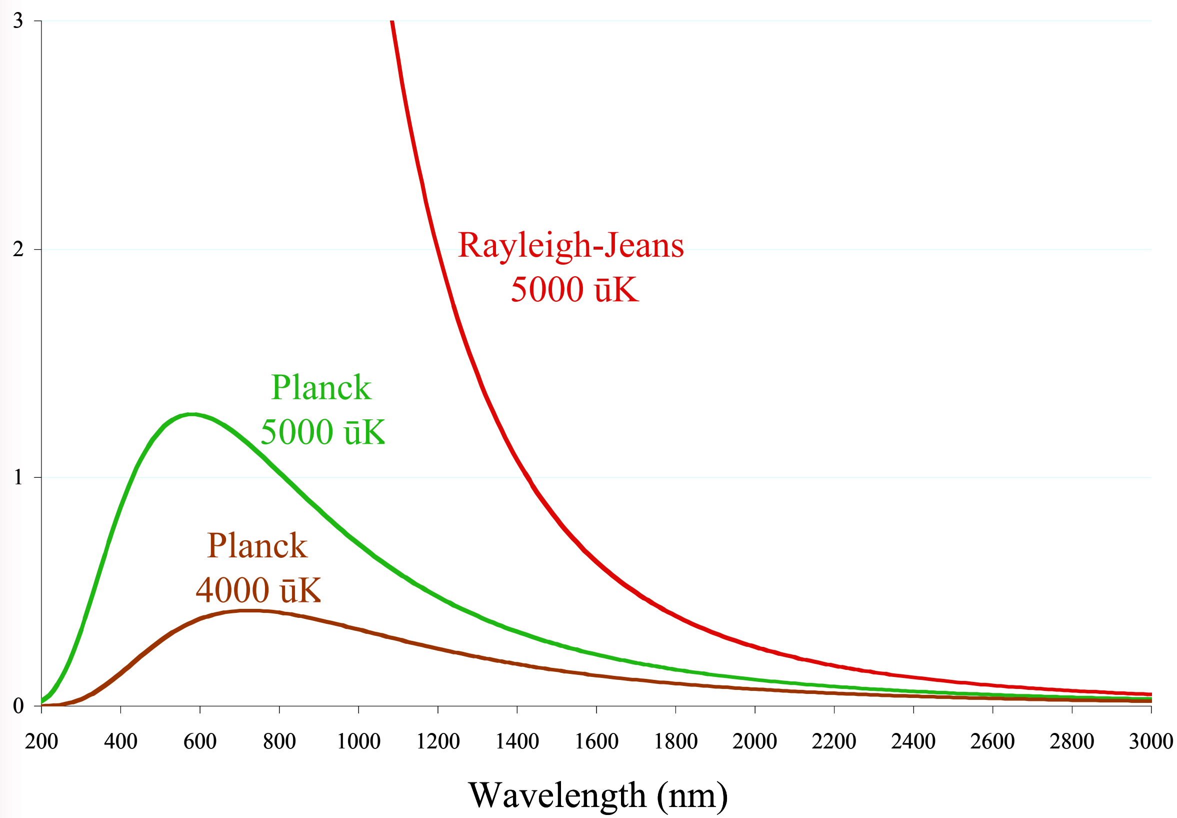
“Everything that can be invented has been invented”

Charles H. Duell

Director, U. S. Patent Office, 1899

Fascinating phenomena began to inspire radical conjectures that led to the development of Quantum Mechanics:

- **1901 Radiation energy distribution (Planck)**



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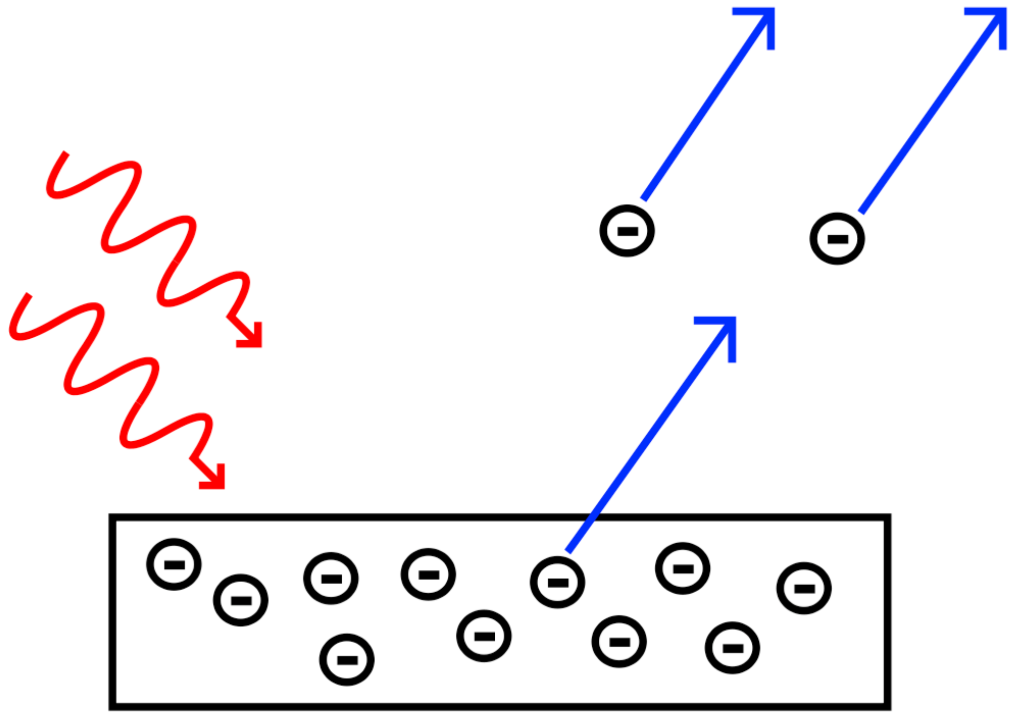

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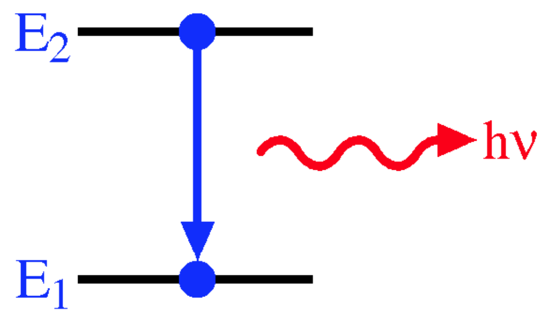
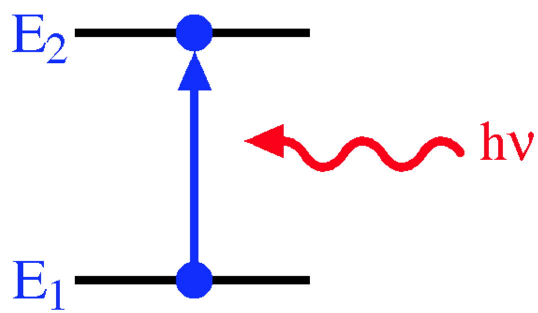
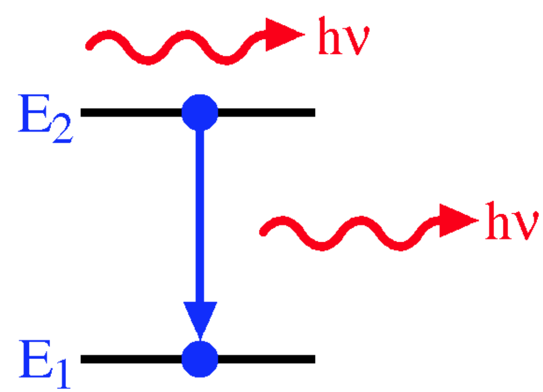


Spontaneous Emission (A)



Absorption (B)



Stimulated Emission (B)

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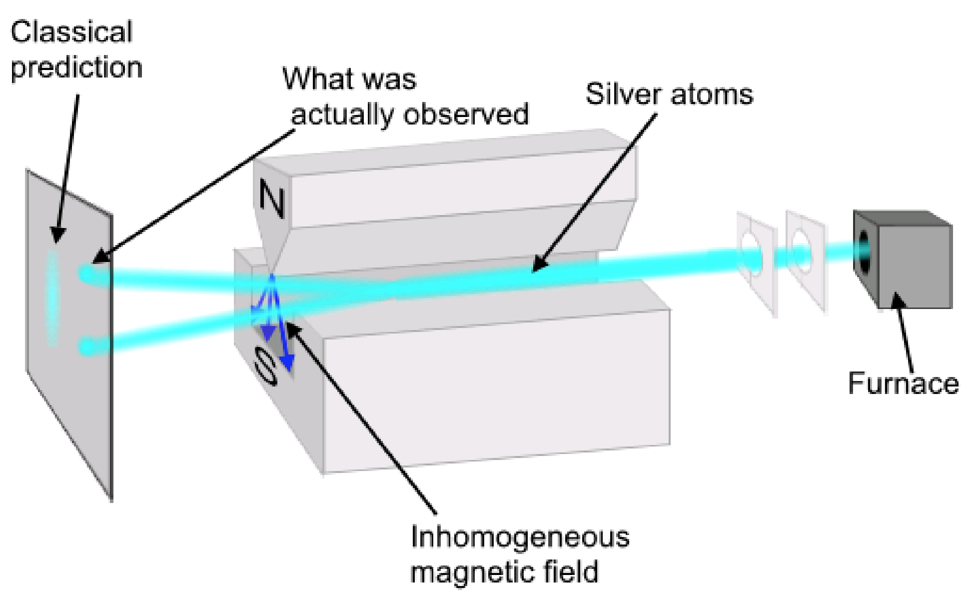
Fascinating phenomena began to inspire radical conjectures that led to the development of Quantum Mechanics:

- 1901 Radiation energy distribution (Planck)
- 1905 Photoelectric effect (Einstein)
- 1917 Light emission and absorption (Einstein A and B coefficients)
- 1922 Electron spin (Stern-Gerlach)



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- **1923 Wave properties of matter (De Broglie)**

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

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$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

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BOTTOM LINE:

The limitations of classical physics had become apparent.

Quantum Mechanics was Born

By the end of the 1920's, there was a great deal of euphoria.

But Einstein was always uneasy about the implications of quantum mechanics.

(Even though he had made seminal contributions to its development)

Letter: Einstein to Max Born

Dated November 7, 1944

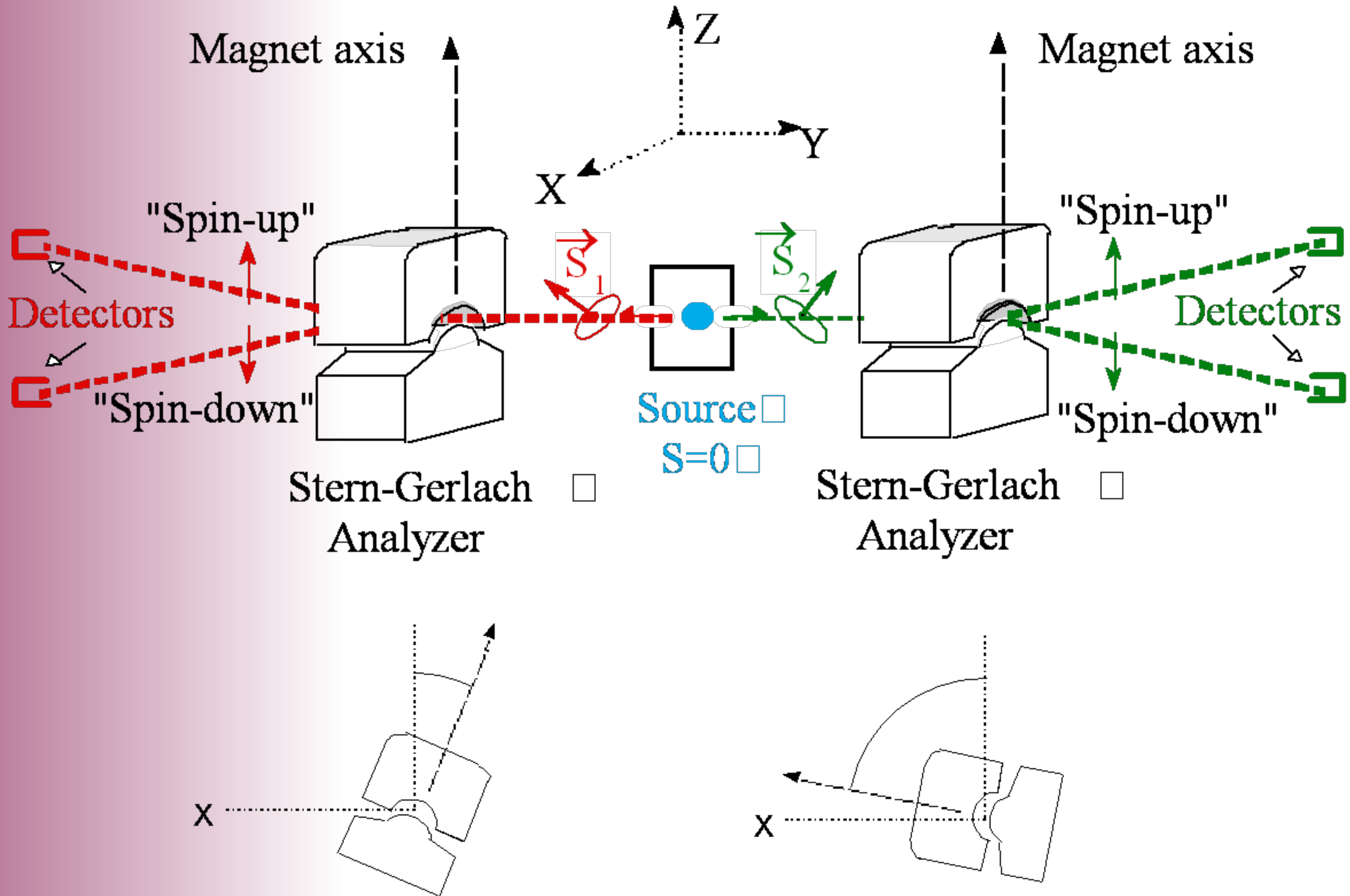
"You believe in God playing dice and I in perfect laws in the world of things existing as real objects. . ."

The EPR paper

Can quantum-mechanical description of physical reality be considered complete?

A. Einstein, B. Podolsky, N. Rosen
Phys. Rev. **47**, *p. 777 (1935)*

Bohm's version of EPR



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

If measurement of the spin of particle #1 in the Z-direction has outcome "spin-up" (+Z), then one can predict with certainty that measurement of the spin of particle #2 in the Z-direction has outcome "spin-down" (–Z). Hence, Einstein would say there is something "real" about the spin of particle #2 in the Z-direction.

Similarly, if measurement of the spin of particle #1 in the X-direction has outcome "spin-up" (+X), then one can predict with certainty that measurement of the spin of particle #2 in the X-direction has outcome "spin-down" (–X). Hence, Einstein would say there is something "real" about the spin of particle #2 in the X-direction.

Since quantum mechanics does not simultaneously encompass two components of the spin, Einstein concludes that quantum mechanics is "incomplete".

Einstein's concern:

If the spin direction of particle #2 in the Z-direction were not a "real" property of particle #2, I believe Einstein's concern was that the measurement on particle #2 would depend non-locally on the orientation of Stern-Gerlach analyzer #1.

Einstein:

Locality requires "hidden variables"

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

John von Neumann:

1932, “impossibility” proof

David Bohm:

1952 did the “impossible”, he produced an example of a “hidden variable” theory

Letter: Einstein to Max Born
Dated May 12, 1952:

“Have you {Born} noticed that Bohm believes (as deBroglie did, by the way, 25 years ago) that he is able to interpret the quantum theory in deterministic terms? That way seems too cheap to me.”

“But you, of course, can judge this better than I.”

For 20 years, scientists believed it was "impossible" to complete quantum mechanics. There were hostile and bitter arguments

Bohm did it, then it was too glib, too simple.

Adding just a few variables would have been a big disappointment to Einstein.

He wanted a big principle to emerge - e.g.
relativity,
conservation of energy

John Bell

Considered an EPR type experiment

Assumed:

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

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

John Bell Proved:

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

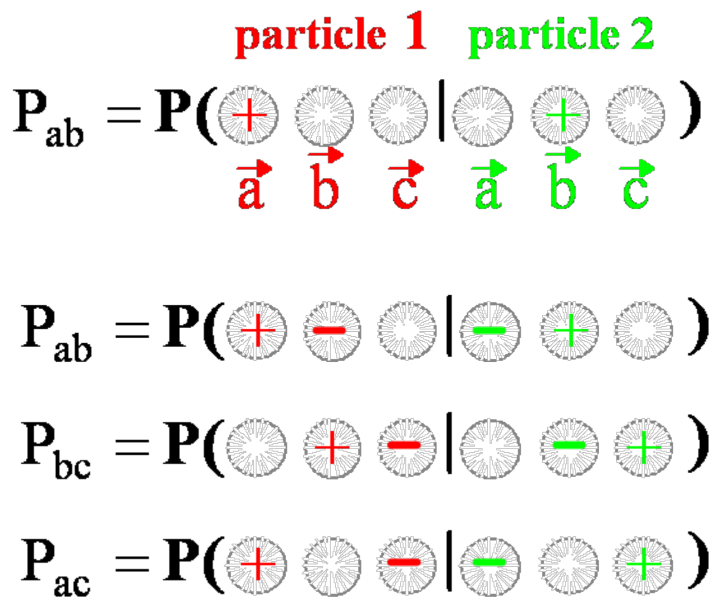
2. **The statistical predictions of quantum mechanics can violate that inequality.**

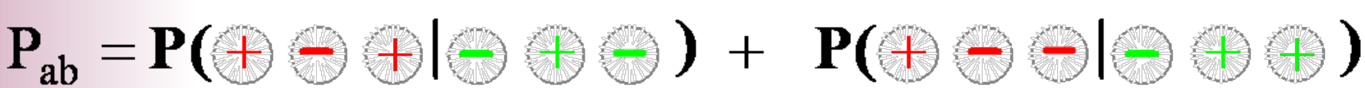
A definitive laboratory experiment is possible

Wigner-Belinfante Derivation of a Bell Inequality

Consider Bohm's version of EPR, take two spin 1/2 particles in a total spin zero (singlet) state.

Define:





$$P_{ab} = P(+\ -\ +) + P(+\ -\ -)$$

$$P_{ab} = P(+\ -\ +) + P(+\ -\ -)$$

$$P_{bc} = P(+\ +\ -) + P(-\ +\ -)$$

$$P_{ac} = P(+\ +\ -) + P(+\ -\ -)$$

$$P_{ab} + P_{bc} = P_{ac} + P(+\ -\ +) + P(-\ +\ -)$$

Hence the Bell Inequality:

$$P_{ab} + P_{bc} \geq P_{ac}$$

Quantum Mechanical Predictions

In quantum mechanics the probability of two particles having spin "up" in directions θ_a and θ_b is

$$P_{ab} = \frac{1}{4}\left\{1 - \cos\left(\theta_a - \theta_b\right)\right\}$$

Take: $\theta_a = 0°$ $\theta_b = 45°$ $\theta_c = 90°$

Then, $P_{ab} + P_{bc} = \frac{1}{2}$ $P_{ac} = \frac{1}{4}$

$$P_{ab} + P_{bc} \geq P_{ac} \implies \frac{1}{2} - \frac{\sqrt{2}}{4} \geq \frac{1}{4} \quad i.e.\ \frac{0.586}{4} \geq \frac{1}{4}$$

The quantum mechanical predictions do not satisfy the Bell Inequality

Physical interpretation of Bell's result:

Any LHV theory restricts the strength of the statistical correlations; there is an upper limit on their magnitude.

Quantum mechanics predicts very strong correlations that can violate the restriction.

Einstein:

Quantum mechanics is an incomplete theory since its predictions for spatially separated systems are incompatible with locality. There must be something more, *e.g.* hidden variables.

locality $\Longrightarrow$ QM is incomplete

Bell:

Quantum mechanical predictions for spatially separated systems cannot be reproduced by any theory that completes quantum mechanics and retains locality.

locality $\Longrightarrow$ QM cannot be “completed”

The IRONY of it all !

Einstein was a strong advocate of locality, and used it, via EPR, to argue that quantum mechanics was an "incomplete" theory. Bell showed it is just the reverse!

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
1980- Paris	violated Bell inequality and agreed with QM

All these previous experiments have had loopholes; they required additional assumptions in order to make the experiment feasible.

Some of the more recent experiments:

Paris -

Entanglement of atoms in high Q microwave cavity

Innsbruck -

Tested Bell inequality with entangled photons under strict Einstein locality conditions

Geneva -

Tested Bell inequality with entangled photons and a detector separation of 10.9 km

Boulder (2001) -

Tested Bell inequality with atoms and high efficiency detection

Austria (2003) -

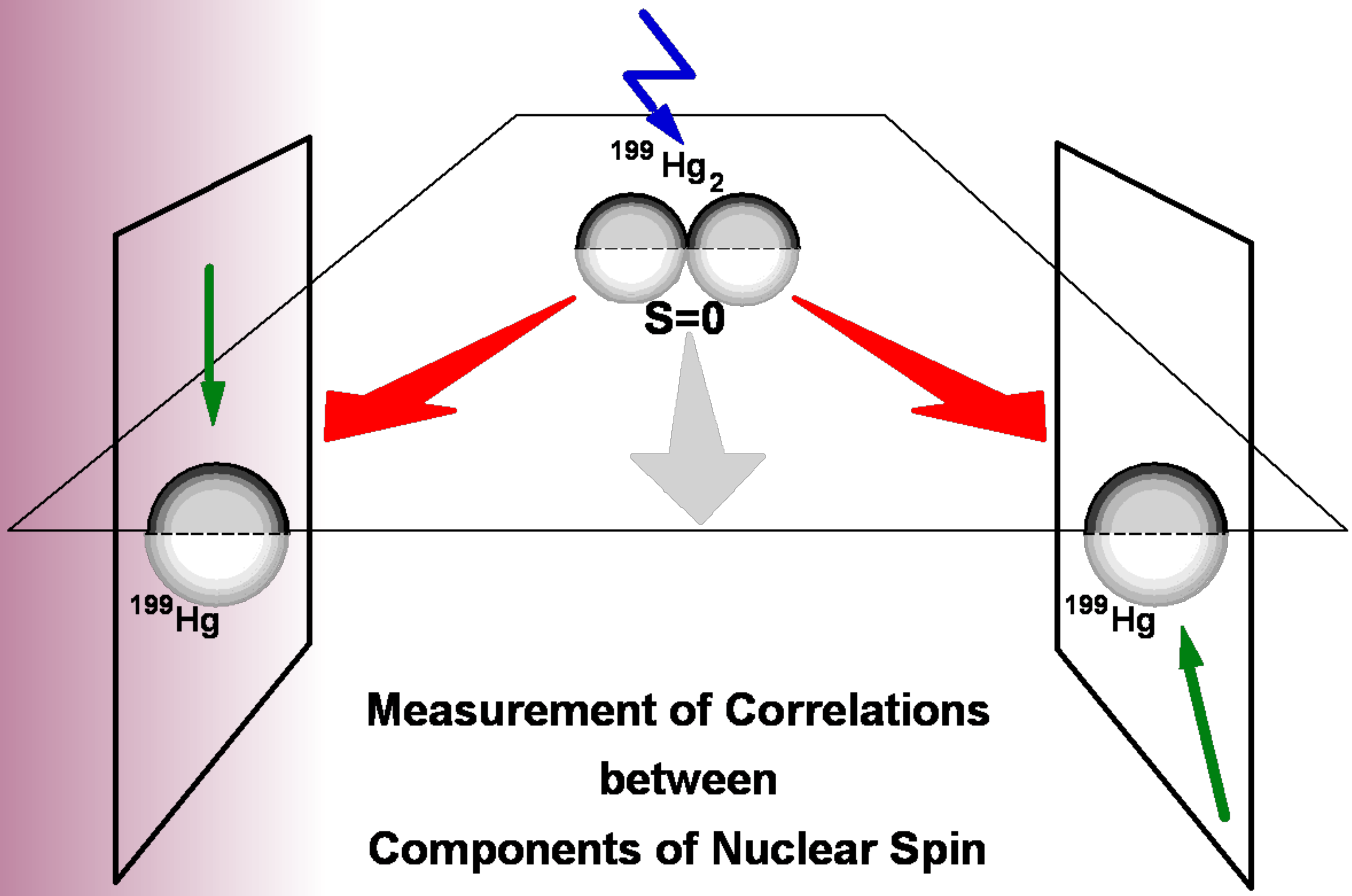
Tested Bell inequality with space and spin components of a single neutron

Note:

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

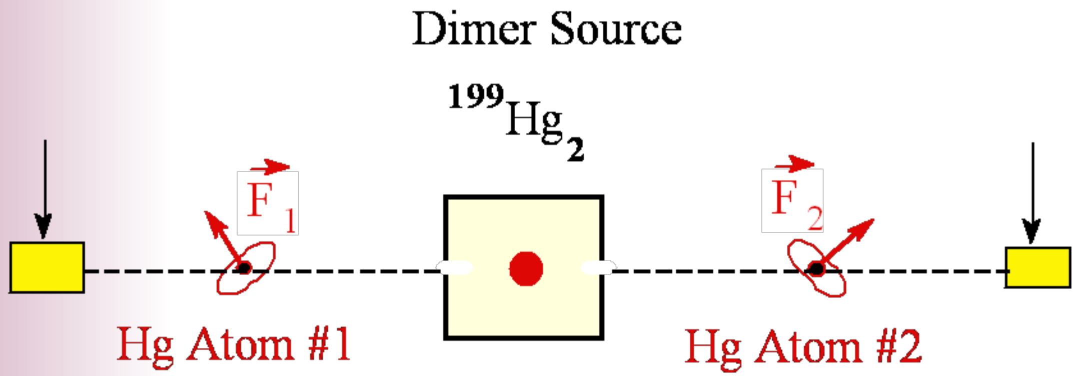
But, results of Bell inequality experiments do <u>NOT</u> require quantum mechanics to be non-local.

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



Features

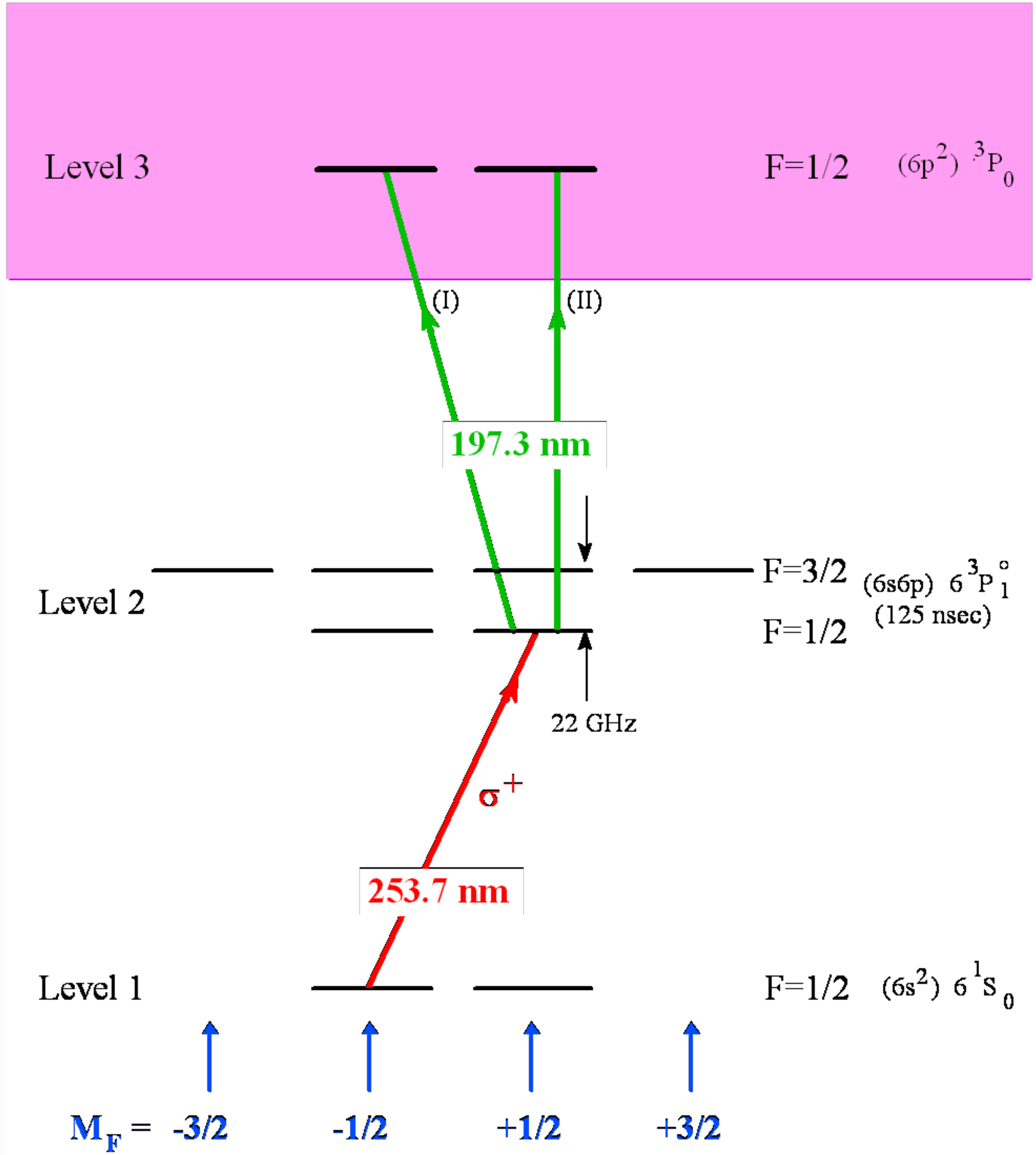
1) Efficient detectors
2) Enforce Einstein locality
3) Spin one-half fermions rather than bosons
4) Massive particles rather than massless photons.
5) Inside the light cone rather than on it.
6) Entangled state exists for milliseconds vs. nanoseconds in photon experiments - a different time scale by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



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

Analyzers determine component of F in a specific direction.

Measure correlations between different components of F.


Level 3
F=1/2 (6p²) ³P₀
(I)
(II)
197.3 nm
Level 2
F=3/2 (6s6p) 6 ³P°₁
(125 nsec)
F=1/2
22 GHz
σ+
253.7 nm
Level 1
F=1/2 (6s²) 6 ¹S₀
M_F = -3/2 -1/2 +1/2 +3/2

THE END