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Verification of Wave-Particle Complementarity by Asymmetrical Double-slit Interference

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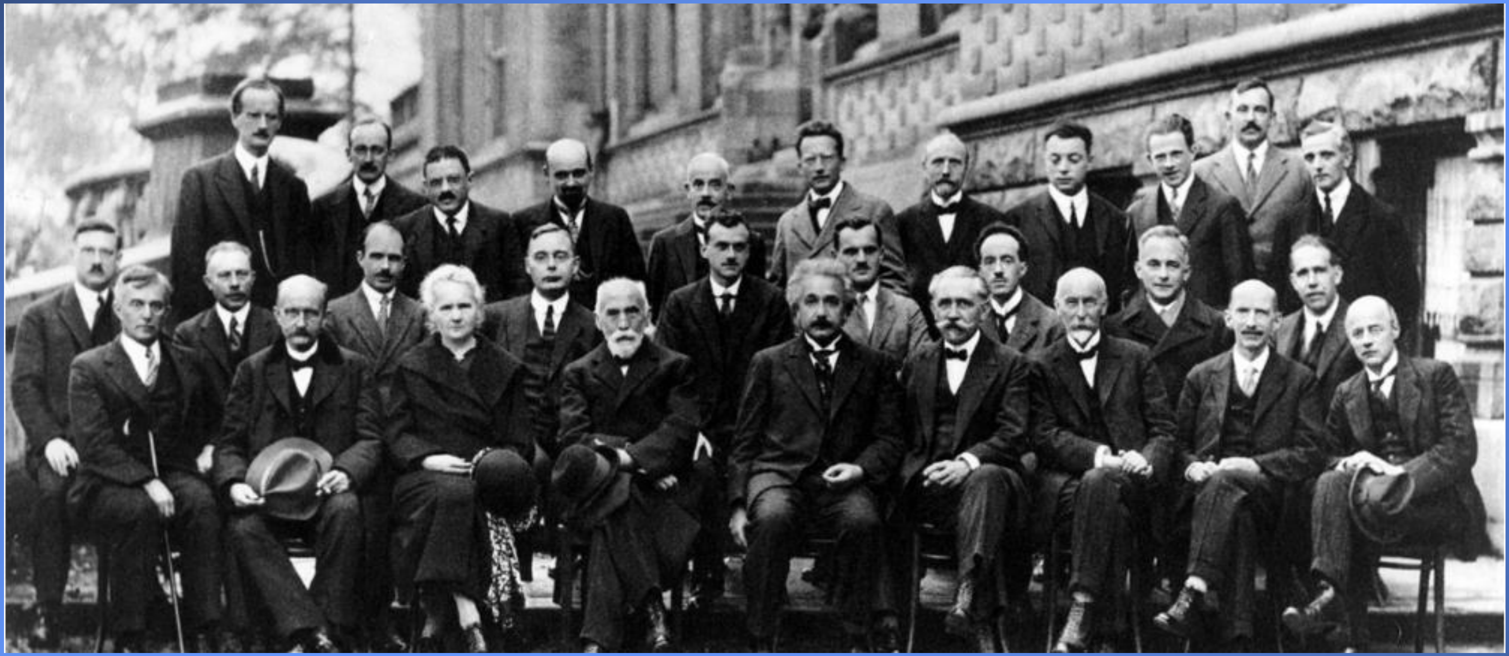
Contents

I- Problem of Quantum Mechanics (1)

1.1-Physical reality (PR) in QM is a conceptual problem of Physics:
Since the 5th Solvey Conference 1927.



- Bohr: the **Complementarity Principle**; and Heisenberg: the **Uncertainty Inequalities**.

Debate:

Copenhagen (Bohr, Heisenberg…) **> <** Einstein (de Broglie, Schrodinger …)

I- Problem of Quantum Mechanics (2)

Physical reality in Quantum Mechanics …:

❑ **Copenhagen scholars** (Bohr, Heisenberg…):

According to the **Complementarity Principle:**

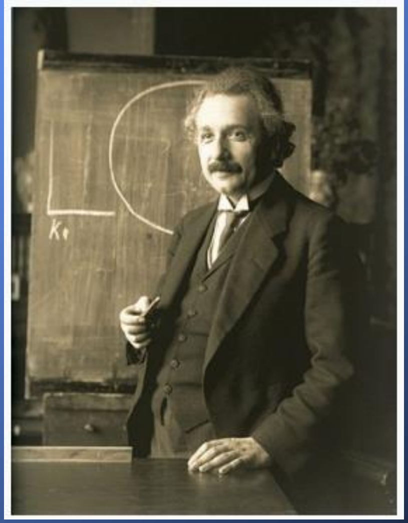
→ **There is no way to observe in the same measurement complementary properties, such as waves and particles!**

→ **Consequently, it is not possible to prove an objective physical reality of quantum matter.**

❑ **Einstein opposition**: QM is correct but seems incomplete (inadequate).

→fighting for complete descriptions to demonstrate the reality of quantum physics.

→e.g. causal interpretation of QM: de Borglie-Bohm (dBB) theory with hidden parameters: duality of the QM Schrodinger equation and a Semi-classical Haminton-Jacobi equation (with Quantum potential Q_B).

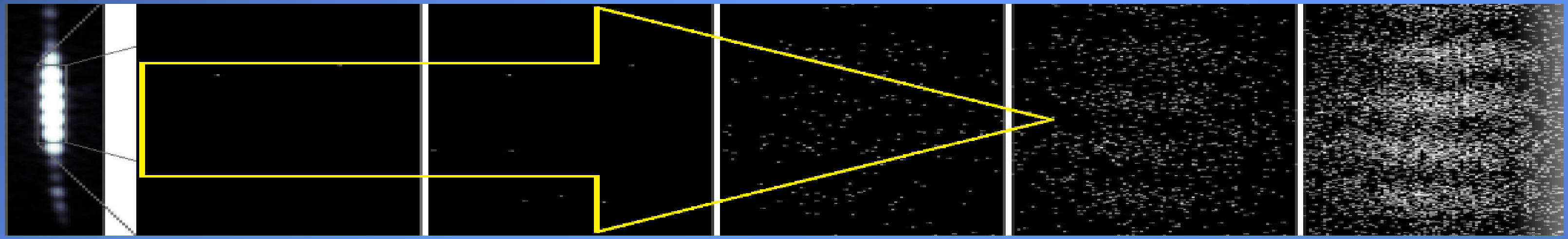


I- Problem of Quantum Mechanics (3)

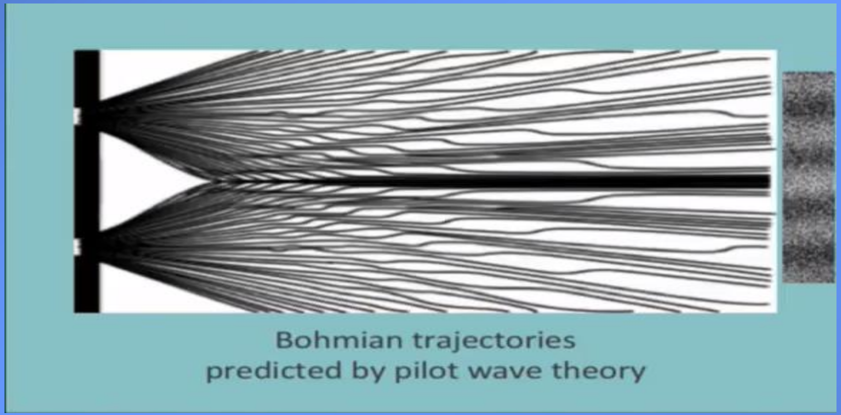
1.2-Importance of Double-slit Experiments:

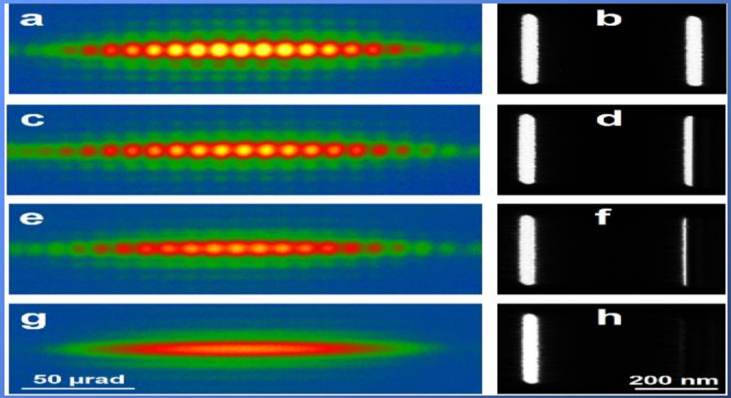
R. Feynman (1965): A thought Double-Slit experiment **with Single particles (Not Multiple)** was proposed **to verify Complementarity Principle**, which is expressed through the Englert-Grinberger-Yasin quadratic correlation (EGY): $\boldsymbol{V^2 + D^2 \leq 1}$

(**V =** Interference **Visibility** and **D =** Which-way **Distinguishability**).



Buildup of **Single-electron interference** by R. Bach et al., New J.Phys. 15(2013)





Feynman-type double-slit experiment.

A. Tavabi et al., Sci.Rep. 9(2019)

→All **Symmetrical double-slit experiments obey the Complementarity Principle !**

II- Concept of Experiment and Analysis (1)

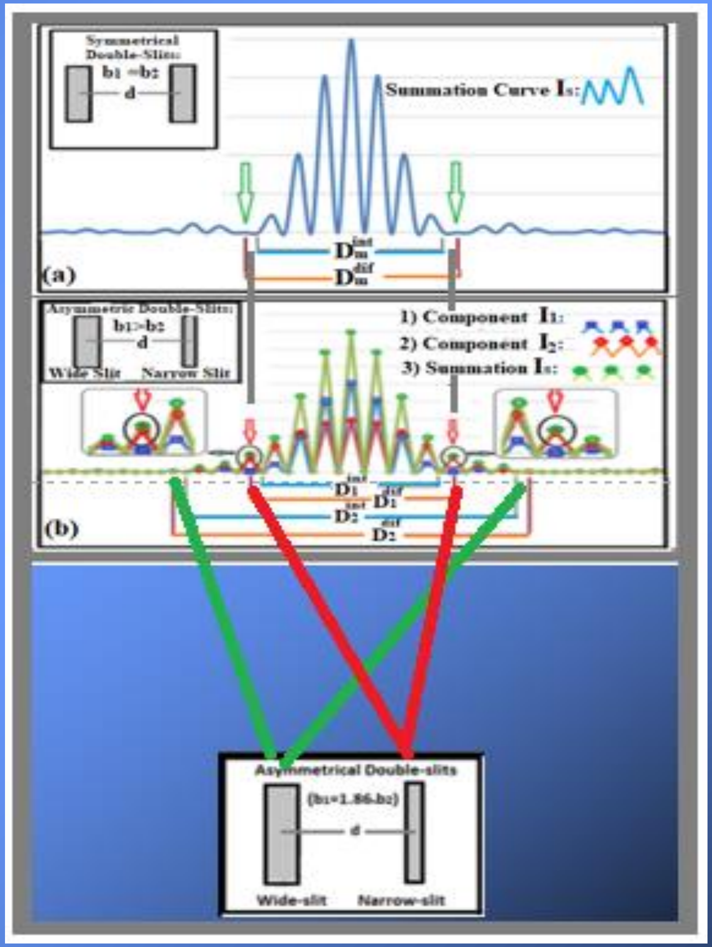
Why do we need the Asymmetrical Double-Slit Experiments?

In our early study [1], a special which-way identifiable method was proposed: in the first main minimum only photons passing through one slit (the narrow) can be observed, i.e.
the path distinguishability D=1.
Moreover, in some spectra a significant amount from these D-photons exhibit interference, i.e. V>0.

→ Does it mean both the Interference and the Path have been observed Simultaneously ?

→ In [1,2], we have not yet quantitatively analyzed the correlation between the two quantities:

the path (particle) distinguishability D and the interference (wave) visibility V.

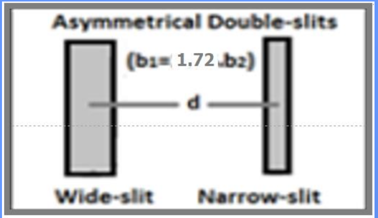


Concept of which-way identification

→ Now the objective of new study is quantitative analysis of D+V correlation !

II-Concept of Experiment and Analysis (2)

- **The experimental Method** bases on the concept of:
- **Single-photon interference (Self-Interference)**,
- and **Asymmetrical Double-slits**,



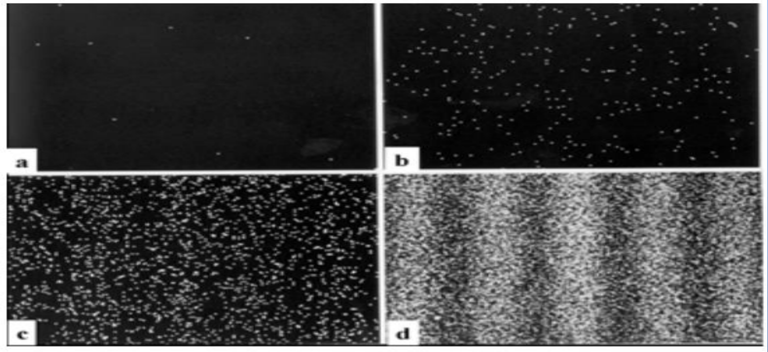
- in **the Far-field Fraunhofer condition:** $N_{Fr} = \frac{b_m^2}{L\lambda.} \approx 10^{-3} \ll 1$.

- **Single photon condition**: Laser Power $W_{Laser} < 0.3\ mW \equiv 10^{15}$ photon/sec, which is due to Laser short time-window:

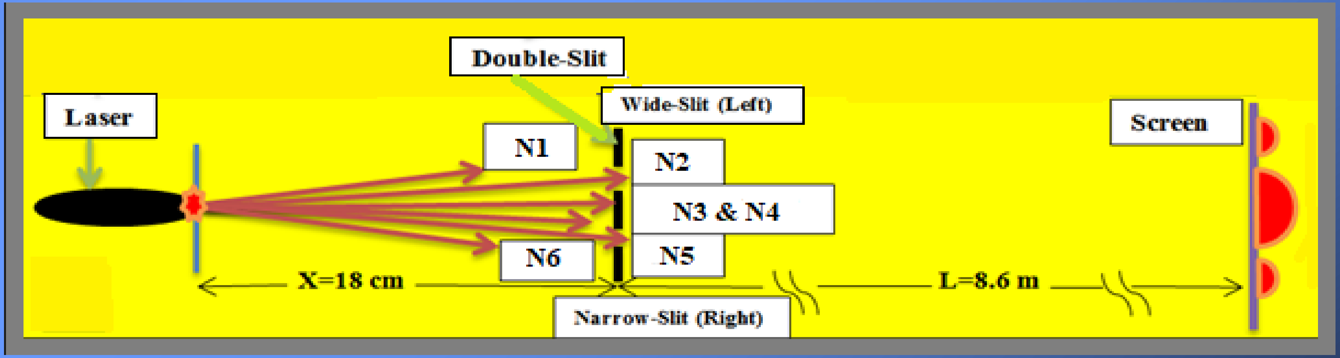
$$\Delta t_{Laser} \approx \frac{\lambda}{2.c} = 10^{-15} sec.$$

(λ=650 nm; c=3.10^5 km/sec).

→ Double-Slit interference of Single photons is **Self-interference**.



Build-up of Single-Photon interference



II- Concept of Experiment and Analysis (3)

For Theoretical calculation: assuming for simplification $a.I_1 > (1-a).I_2$. (1)

- The **summation diffraction intensity** (without interference fringes):

$$I_S(x) = a.I_1(x) + (1-a).I_2(x), \qquad (2)$$

- The **summation spectrum with interference** consists of two mixed parts:

$$I_S^{int}(x) = D(x) + V^{int}(x). \qquad (3)$$

where D(x) is **particle distinguishability** and V(x) is **wave visibility**.

- **Complementarity Menon-Qureshi (M&Q) correlation, Phys.Rev. A98(2018):**

$$D(x) = D_Q(x) = |a.I_1(x) - (1-a).I_2(x)|. \qquad (4)$$

$$V^{int}(x) = 2.(1-a).\sqrt{I_1(x).I_2(x)}.G(\sigma,x), \qquad (5)$$

→ the complementarity correlation has a new simplified form: **D_Q+V=1** .

- **The de Broglie-Bohm (dBB-) theory:**

$$D_B(x) = \Delta I_1 = aI_1(x) - (1-a)I_1(x) = (2a-1).I_1(x). \qquad (6)$$

$V^{int}(x) = (1-a)[I_1(x) + I_2(x)].G(\sigma,x)$. (7) / $G(\sigma,x)$ is Normal Gaussian

→ Investigation of **D+V in the first main minimum at j=7.**

III- Data Processing (1)

- We use the asymmetric double-slit interference spectra N1-N6 obtained in our previous experiment [2].

- We perform a summation of the left and right sides of each experimental spectrum to minimize systematical uncertainties due to any left-right asymmetry, in particular, for N1 and N2.

- Surveys and spectral analysis are performed **in an effective range** of the interference fringes **from j=6 to j=13** with enough low optical density to **control photo-camera's dead time** and any noises from **multi-photon interference**.

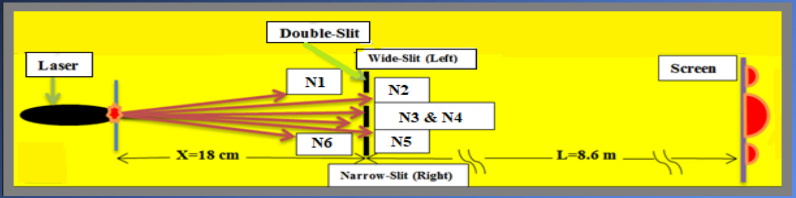
- Moreover, we redefine the relative intensity a (= I_1 %) and 1-a (= I_2 %) of two components I_1 and I_2 by fitting the diffraction distribution

$$I_S(x) = a.I_1(x) + (1-a).I_2(x), \quad (2)$$

in the effective range (from j=6 to j=13).

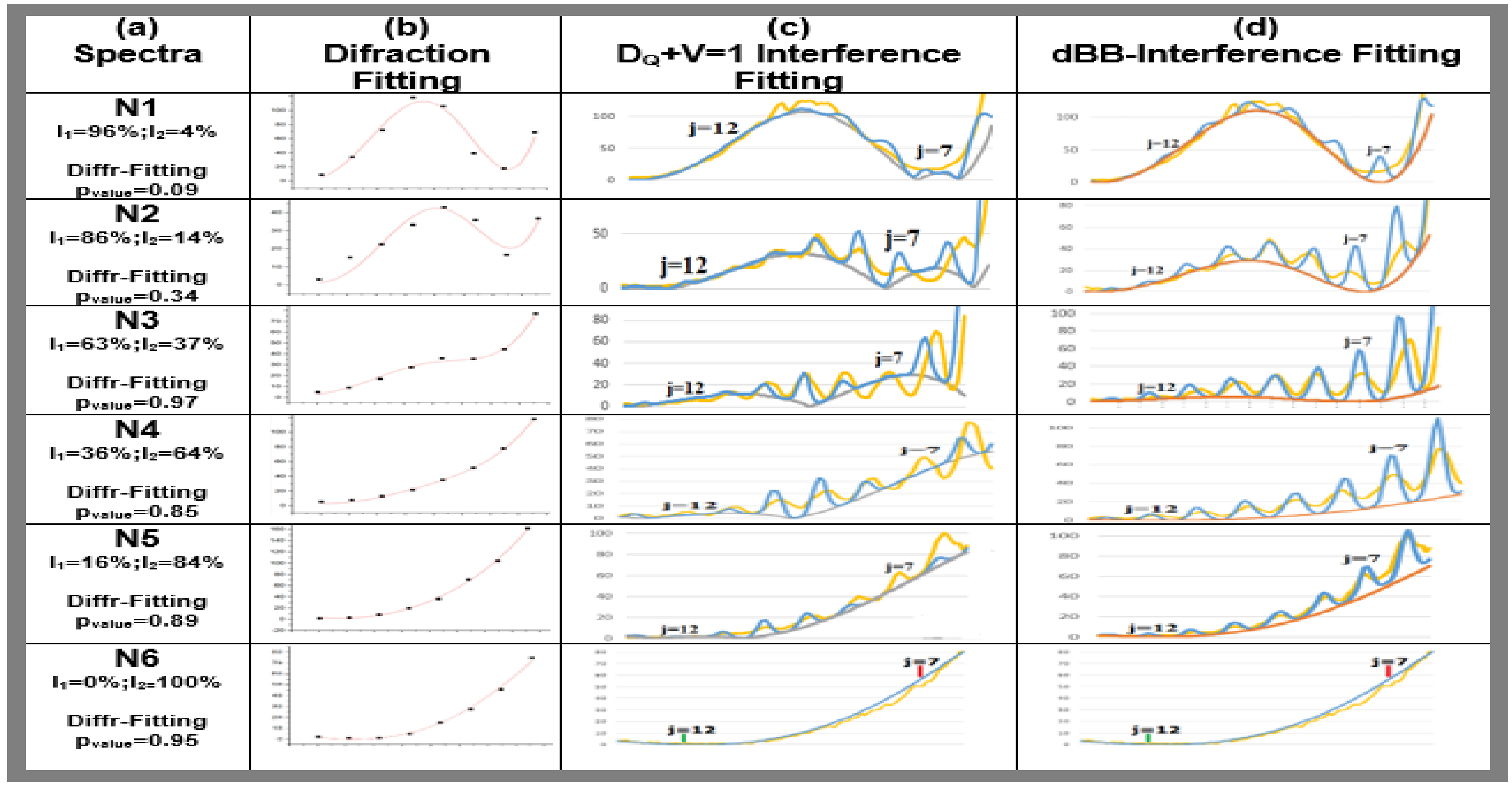
III- Data Processing (2)

❑ **Analysis with an ideal interference-fringe resolution ($\sigma = \pi/7$)**



$$I_S(x) = a.I_1(x) + (1-a).I_2(x), \quad (2)$$

→**Parameter a%=I1** and **(1-a)%=I2** are used for calculation of interference spectra N1-N6.



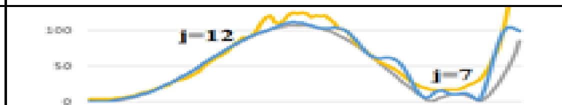
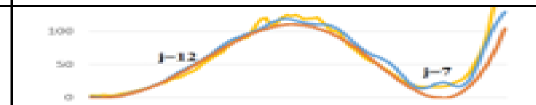
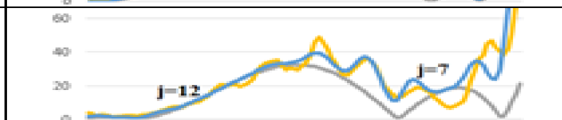
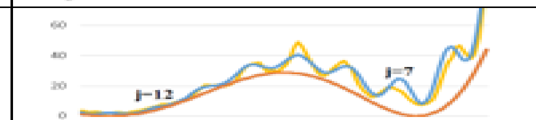
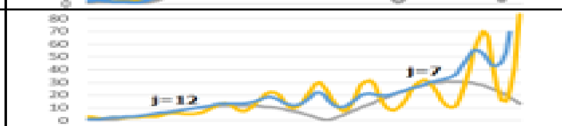
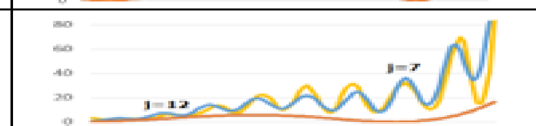
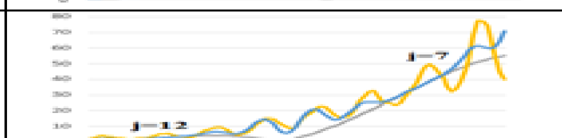
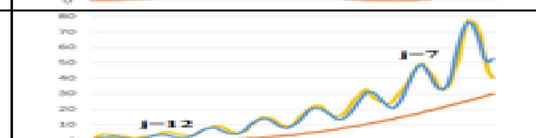
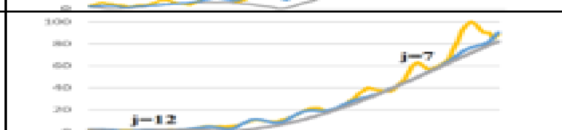
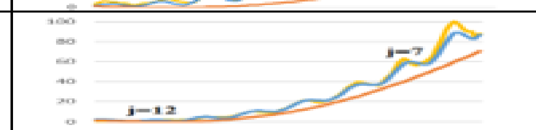
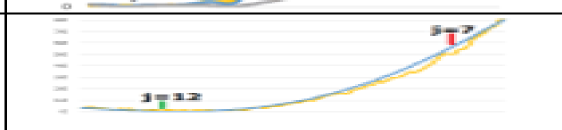
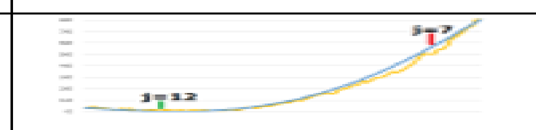
Fitting with an ideal resolution ($\sigma = \pi/7$)

→ **M&Q** interpretation (c) and **dBB** (d): **both theories are rejected**.

III- Data Processing (3)

- **Analysis with the realistic interference-fringe resolution (σ= π/4)**

$$I_S^{int}(x) = D(x) + V^{int}(x). \qquad (3)$$

Spectra	(a)-D_Q+V=1 Fitting	(b)-dBB-Fitting	(c)-DOF p-value for dBB
N1 I_1=96% I_2=4%			87 0.31
N2 I_1=86% I_2=14%			95 0.97
N3 I_1=63% I_2=37%			85 0.42
N4 I_1=36% I_2=64%			96 0.99
N5 I_1=16% I_2=84%			88 >0.99
N6 I_1=0% I_2≈100%			94 >0.99

χ^2_ν-test with the **realistic resolution** (σ= π/4)

(a)-by **M&Q** interpretation: Not consistent.

(b)-by **dBB theory**: Good consistency→all p-values>0.05, (for N3 p=0.42 ?)

IV- Discussions (1)

4.1-Case study: Spectrum N3

- **(a)-M&Q-Theoretical interpretation**. At j=7 with $\boldsymbol{I_V = 0}$ which leads to:

$$\frac{I_D+I_V}{I_S} = D_Q + V_Q = 1 + 0 = D_Q$$

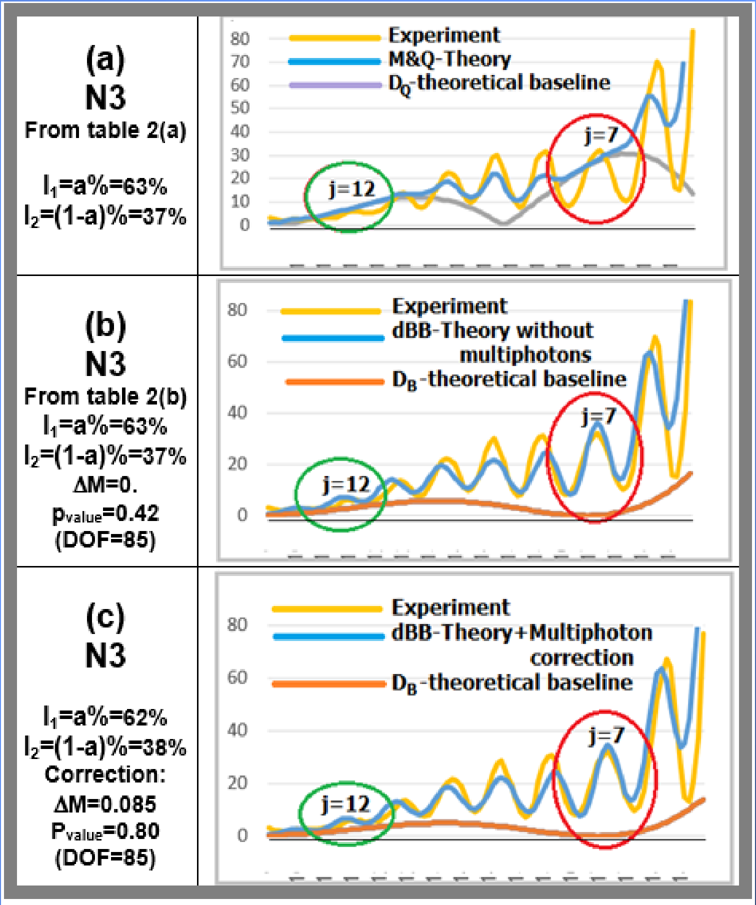
- **(b)- dBB-Theory** (p-value 0.42 relatively lower than other p-values?). But, at j=7, dBB shows $\boldsymbol{I_V \neq 0}$ – as **an excess**, leading to:

$$\frac{I_D+I_V}{I_S} = D = 1 \rightarrow \ (D+V)_{Theor} = 1.50$$

- **(c)**-The same **dBB-Theory, but with the 8.5%-Multiphoton correction (a=62%):** (χ_v^2 =74/DOF=85→**p-value 0.80** improves consistency). At j=7 it leads to the same theoretical value, thus multiphoton correction doesn't affect (j=7)-fringe: **(D+V)Theor=1.50 (Multiphoton correction).**

→Theoretical is consistent with Experimental:

(D+V)Exp=1.54±0.08

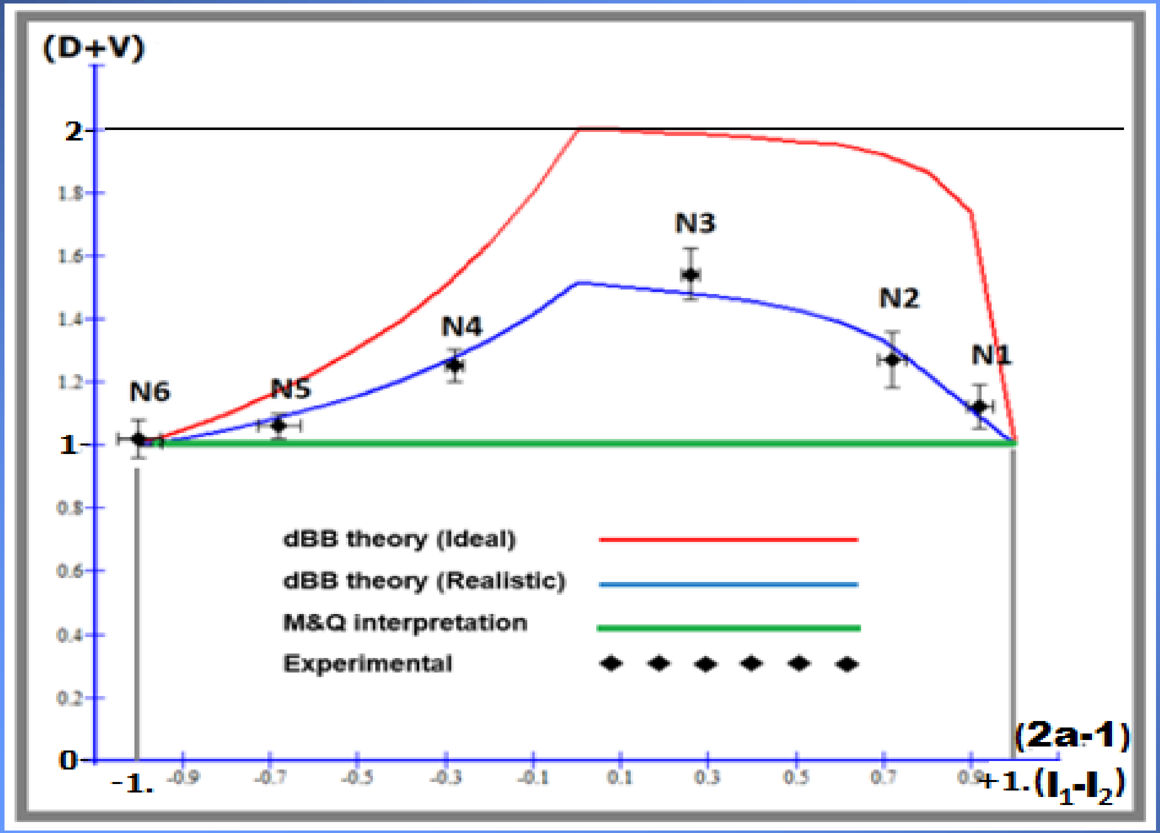


χ_v^2-test with an realistic resolution (σ=π/4) for N3 spectrum.

The ovals show two main minima of I_1 (Red) and I_2 (Green)

IV- Discussions (2)

- Following calculation of (D+V) for N3, the same way for other spectra:



The (D+V)-correlations at the interference order with j=7
M&Q theory (Green line), **dBB theory** with **realistic resolution** (Blue curve)
and **dBB theory** with **ideal resolution** (Red curve)
in **reference to experimental N1-N6** (Black rhombuses).

Only dBB blue curve with **σ= π/4** fits experimental (χ^2_ν =1.78/DOF =5→**p-value > 0.90**)

V- Conclusions (1)

- Regarding the Problem of **Physical Reality** in Quantum Mechanics, we perform an **Asymmetrical double-slit** experiment in the **Far-field Fraunhofer condition** with a constraint of **Single-photon interference**.

- The **Menon-Qureshi interpretation of Complementarity** has helped confirm that it is possible to create **special locations in the first main minima** in the asymmetrical double slit interference spectrum at which the **particle nature can be revealed maximally, i.e.** $D_Q=1$.

However, it is **not possible to further explain the occurrence of interference fringes at those spectral main minima based on M&Q correlations** alone.

- Instead, **interpretations according to dBB theory have solved this very well**.
  →Under proper resolution adjustment for interference fringes ($\sigma=\pi/4$),

the **dBB-theoretical curve achieves high consistency** with **experimental data**.

V– Conclusions (2)

- The obtained correlation **D+V > 1** reconfirms that :

The asymmetrical double-slit experiment would be an effective way to measure **simultaneously both the path and the interference** of single photons **without any disturbance** of the laser beam.

- For perspectives,

- More data measured at the main minima would be desirable to fill the gaps in the region around the orthogonal direction of the laser beam of high coherency, where interference visibility approaches a maximal value, i.e. V→1 and (D+V)→2.

- Furthermore, the experiments have been conducted with the assumption of single-photon condition, but it is an approximation, so it is necessary to carry out new studies with standard single-particle sources, which could be single photons or single electrons.

Acknowledgement

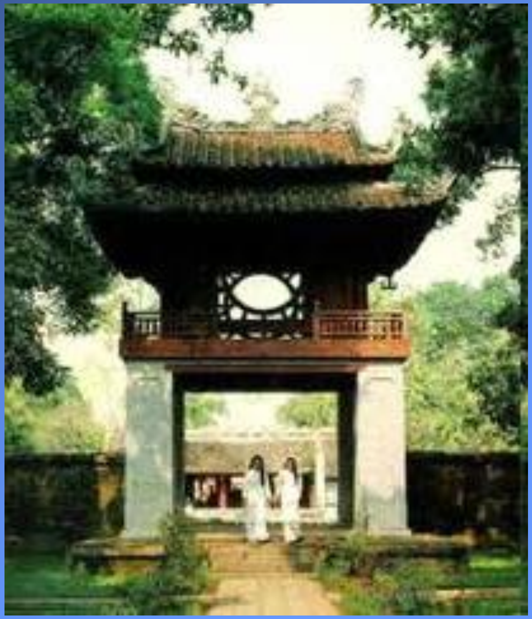
Co-authors of the present research from the Vietnam Atomic Energy Institute (VINATOM) are Vu Duc Vinh, Nguyen Thanh Hung and Dang Quang Thieu.

The presenter (V.V.Th.) deeply thanks them for their hard work and fruitful cooperation.

References:

[1] Vo Van Thuan. A possible solution to the which-way problem by asymmetrical double-slit experiments. **Physica Scripta 96 (2021)12510 1-20**.

[2] Vo Van Thuan, Vu Duc Vinh. Which-way identification by an asymmetrical double-slit experiment with monochromatic photons. **Scientific Reports 12 (2022)1008 1-10**.



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