Bacteria as Quantum Clocks

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Abstract: In this study we have investigated the biological application of Wigner’s inequalities for smallest quantum clock. We have shown that the mass, size and doubling time of bacteria satisfied the Wigner’s inequalities for quantum clock. Data on 17 bacteria with mass $1 \times 10^{-15} - 1 \times 10^{-17}$ kg, size $0.3$-$50 \mu$m and doubling time $1 \times 10^3 - 1 \times 10^5$ seconds confirmed the hypothesis of Pešić that possibly the living bacteria appear to be the smallest quantum clocks in the Nature.

Keywords: Time, Quantum Clock, Wigner Inequality, Bacteria

Introduction

The application of quantum mechanics to biological systems is of great interest for theoretical and experimental areas of biological sciences. One spatial case of application of quantum mechanics is to examine the living cells and bio-molecules as ‘quantum clocks’. The ‘quantum clock’ is a concept developed by Wigner and Salecker (1957; 1972) for the non-living physical systems. Later this concept was applied for black hole (Barrow, 1996), living cells (Pešić, 1993) and cellular enzymes (Goel, 2008). The Pešić model of bacteria as ‘quantum clock’ is supported on inequalities of Wigner (Salecker and Wigner, 1958) for a smallest clock with maximum size ‘$L$’ and mass ‘$M$’. Based on quantum mechanical considerations these scientists found that the longest Time ($T$) for a clock that can remain accurate is presented by ‘the first inequality’:

$$T < \frac{M \lambda^2}{\hbar}$$

(1)

where, $\hbar = 1.05 \times 10^{-34}$ J·s is the Planck’s constant and $\lambda$ is the spread in position of the clock during time $T$. The smallest time interval that a clock can accurately measure ($\tau$) is presented ‘by the second inequality’:

$$\tau > \frac{T / \tau (\hbar / Mc^2)}{2}$$

(2)

where, ‘$c$’ is the speed of the light and $T \tau$ is the number of tick of the clock, during the time.

Pešić (1993) first considered the possibility of extending the concept of the clock to biological systems. He observed that in the case of mycoplasmas with cell mass $M = 8 \times 10^{-17}$ (kg) and reproduction (doubling) time $T = 50$ (min) the calculated $\lambda$ is greater than $0.07 \mu$m. The calculated value of $\lambda$ is near to the experimentally measured diameter of the mycoplasma of $0.3 \mu$m. The conclusion of Pešić was that the cell parameters of mycoplasmas are consistent with inequality (1) and the mycoplasmas actually behave as Wigner clocks with accuracy of $10^{-16}$s.

Against this concept there is contradiction (Brualla, 2013). Brualla concluded that the current experimental evidence does not support the validity of Wigner inequalities in a biological context. Thus, this problem remains open for resolution. In this work we support the biological application of Wigner’s inequalities by wide range of experimental data on Prokaryotes (bacteria).

Working Hypothesis

During growth and dividing of cells by binary the cellular parameters (mass, size and form) of the mother and the daughter cells differ slightly, because of the genetic program in the cells. Genetic program determines the cellular mass and size of the daughter cell, but does not determine the doubling time for which the mother’s cell grows and divided by binary. The duration of the doubling time depends on many external parameters (temperature, food sources, pH, ion composition of environment, type of power source) and other factors, which are not under genetic control of the mother’s cell. In this sense the doubling time of the cells appears to be non-defined and relatively random parameter that could be changed in given defined time interval. This time interval must be around the quantum limit of longest doubling time for cellular division. This is possibly as living cells work principally as quantum clocks. This means that during
bacterial growth the cell size changes continuously similarly to the spread \( \lambda \) in position of the quantum clock. The calculated by Pešić (1993) maximum spread \( \lambda = 0.07(\mu m) \) is very near to the volume to surface ratio of mycoplasma, about \( -0.05\mu m \). For example, for spherical mycoplasma with diameter \( D \approx 0.3 (\mu m) \) the volume to surface ratio is equals to \( D/6 \).

Similarly to that in our calculations as more representative length we take the volume to surface ratio of bacterial cells (thus, we considered that maximum spread \( \lambda \) is equals to volume to surface ratio of bacteria). The other argument in favor of the volume to surface ratio as representative length is the relatively constant value of volume to surface ratio during cell growth and dividing by binary (Atanasov, 2012). Because of that, we calculate the bacterial time-characteristics \( (T \text{ and } \tau) \) as function of bacterial Mass \( (M) \), size \( (V/S) \) and Planck constant \( (\hbar) \), accordingly to Wigner equations.

**The Aim of the Study**

- The aim of the study is to calculate the smallest \( (\tau) \) and the longest \( (T) \) times, accordingly to Wigner equations, using data for bacterial mass, size and doubling time
- To identify the real bacterial time-parameters, that correspond to this calculated smallest \( (\tau) \) and longest \( (T) \) Time
- To show that the real bacterial parameters satisfy the Wigner equations for quantum clock

**Methods and Data**

We calculated the longest time interval \( 'T' \) for a quantum clock, accordingly to Equation 1, taken the equality:

\[
T = M \lambda^2 / \hbar
\]

(3)

The calculated values of \( T \) were compared with the doubling time \( T_d \) of bacterial cells, taken from the reported sources.

We calculated the smallest time interval \( '\tau' \) for a clock accordingly Equation 2, using the data for the longest time \( T \), bacterial mass \( M \), the speed of light \( c = 3\times10^8 m/s \) and the Planck constant \( \hbar = 1.05\times10^{-34} J\cdot s \):

\[
\tau = (T / \tau)(h / Mc^2)
\]

(4)

For this purpose, the formula (4) can be presented as the equation:

\[
\tau^2 = Th / Mc^2
\]

(5)

On Table 1 are given the data for 18 bacteria with small, middle and big body mass. The doubling time, size and shape of bacteria are given too. The data for bacterial mass, size and doubling time were taken from scientific publications and sources (Furness and de Maggio, 1972; Waites and Talkington, 2004; Boatman and Kenny, 1970; Razin and Cosenza, 1966; Stemler et al., 1987; Gusev and Mineeva, 1985; Schlegel, 1985; Salser et al., 1968; Gouin et al., 1999; Finster et al., 1992; La Riviere and Schmidt, 2006; Bock, 1976; Starr and Schmidt, 1981; Higgins et al., 1973).

The bacterial volume to surface ratio \( (V/S = \lambda) \) was calculated using the data for the size and shape of bacteria, accordingly to the standard formulas, used for algal cells (Hillebrand et al., 1999; Sun and Liu, 2003). On Fig. 1 are given the main bacterial shapes, the geometric parameters and formulas for calculation of volume and surface of bacterial cells. The shape of bacteria was present as sphere, short cylinder, long cylinder and disk. The small bacteria have predominantly spherical shape until the longest bacteria have the form of long cylinder.

If we replace \( \lambda \) with \( V/S \) ratio, the Equation 3 takes the form:

\[
T = M(V/S)^2 / \hbar
\]

(6)

The smallest time interval was calculated by the equation:

\[
\tau^2 = Th / Mc^2
\]

(7)

where, \( T \) is calculated by the Equation 6. Thus, the Equation 6 and 7 represent the working formulas.
Results

On Table 1 the bacterial mass varied about $10^5$ folds from $1 \times 10^{-17}$ kg in Mycoplasma mycoides to $7 \times 10^{-15}$ kg in Spirrohaeta lutea. The size varied about $2 \times 10^2$ folds from smallest Mycoplasma with diameter 0.3 µm to longest Spirrohaeta with length 50 µm. The doubling time varied about $3.6 \times 10^2$ folds from 20 min in Escherichia coli to 30 h in Thiobacillus thiofmarus.

On Table 2 are given the calculated smallest and longest time intervals of the bacteria, according to Equations 3-5. The smallest time interval ‘r’ gives the accuracy of bacterial clocks, whereas the longest time ‘t’ gives the running time of bacterial clock.

On Fig. 2 are presented the data for $T(t)$, $T_d(s)$ and $r$ (s) as function of bacterial body mass M (kg).

On Fig. 2 the calculated values of bacterial clock accuracy ‘r’ lies below the line of $ATP$ time varied about $3.6 \times 10^2$ longs. $E_{ATP}$ is the free energy of $ATP$ molecule, calculated by the time-energy uncertainty principle:

$$T_{ATP} \times E_{ATP} \geq h$$  \hspace{1cm} (8)

where, $E_{ATP} = 6.0 \times 10^{-21}$-6.0 $\times 10^{-20}$ (J) is the free energy of one $ATP$ molecule (Minkov, 1991) and $h = 6.626 \times 10^{-34}$ (s) is the Planck constant. The mean accuracy of the bacterial clock $T_{mean} = 6.65 \times 10^{-16}$ (s) lies near to the time of $T_{ATP} = 1.1 \times 10^{-16}$ (s), corresponding to the energy of $E_{ATP} = 6.0 \times 10^{-18}$ J, calculated by time-energy uncertainty principle:

$$T_{ATP} \times E_{ATP} \geq h$$  \hspace{1cm} (9)

In this case the equality $T_{ATP} = T_{mean}$ is valid (with error less than one order of magnitude), where any given value of $r$ satisfied the second Wigner’s inequality in the form of $r > T_{ATP}$.

On Fig. 2 the calculated mean value of the longest (running) time $T_{mean} = 6.88 \times 10^4$ (s) lies near to the mean value of the bacterial doubling time $T_{d, mean} = 2.82 \times 10^4$ (s). The minimum and maximum values of the doubling time $(T_{d, min}, T_{d, max})$ are given by two dashed lines. The mean of the calculated values for T falls between $T_{d, min}$ and $T_{d, max}$ lines. Between the mean value of doubling time $T_{d, mean}$ and the mean value of the calculated running time $T_{mean}$ almost equality $(T_{d, mean} \approx T_{mean})$ is valid, where any given value of $T$ satisfied first Wigner’s inequality in the form of $T < T_{d, max}$. In additional, between the calculated longest time $T$ and the experimental values of $T_{d}$, a relatively good correlation (with correlation coefficient $R = 0.47$) exists.

Table 1. Data for mass $M$, size $(D, h, L)$, shape and doubling time $(T_{dt})$ of bacteria

| Bacteria (°C) | Mass M(kg) | D = 0.3 | L-length | Shape | Doubling time $T_{dt}$ (min) |
|--------------|------------|---------|-----------|-------|-----------------------------|
| 1. Mycoplasma mycoides (37°) | 1.55 $\times 10^{-17}$ | sph | 60 |
| 2. Mycoplasma pneumoniae (37°) | 6.91 $\times 10^{-17}$ | 1 cyl | 73 |
| 3. Mycoplasma felix (37°) | 4.32 $\times 10^{-17}$ | disc | 60-87 |
| 4. Mycoplasma hominis (35°) | 3.88 $\times 10^{-17}$ | sph | 60 |
| 5. Mycoplasma arthritidis (37°) | 1.55 $\times 10^{-17}$ | sph | 20-120 |
| 6. Ureaplasma urealyticum (37°) | 2.75 $\times 10^{-17}$ | sph | 74 |
| 7. Bdellovibrio bacteriovorus (35°) | 7.77 $\times 10^{-17}$ | sh cyl | 20-300 |
| 8. Walbachia melophagi (35°) | 4.62 $\times 10^{-17}$ | sh cyl | 25-300 |
| 9. (a) Staphylococcus aureus (37°) | 1.24 $\times 10^{-16}$ | sph | 23-120 |
| (b) Staphylococcus aureus (37°) | 5.76 $\times 10^{-16}$ | sph | 309 |
| 10. (a) Bacillus subtilis (37°) | 2.16 $\times 10^{-16}$ | sh cyl | 225 |
| (b) Bacillus subtilis (37°) | 3.45 $\times 10^{-16}$ | l cyl | 225 |
| 11. Escherichia coli (37°) | 1.38 $\times 10^{-16}$ | sh cyl | 20-150 |
| 12. Rickettsia prowazeki (37°) | 6.22 $\times 10^{-17}$ | sh cyl | 480 |
| 13. Rickettsia conorii (37°) | 6.22 $\times 10^{-16}$ | l cyl | 480 |
| 14. Thiobacillus thiofmarus (30°) | 6.47 $\times 10^{-16}$ | sh cyl | 2000 |
| 15. (a) Spirochaeta lutea (35°) | 4.32 $\times 10^{-16}$ | l cyl | 240 |
| (b) Spirohaeta lutea (35°) | 7.0 $\times 10^{-15}$ | l cyl | 240 |
| 16. (a) Nitrobacter agilis (35°) | 1.3 $\times 10^{-16}$ | sh cyl | 420 |
| (b) Nitrobacter agilis (35°) | 5.53 $\times 10^{-16}$ | sh cyl | 420 |
| 17. Lactobacillus acidophilus (37°) | 9.1 $\times 10^{-17}$ | sh cyl | 45 |

* sph-sphere; sh cyl - short cylinder; l cyl - long cylinder
Table 2. Calculated data for volume to surface ratio ($\lambda$), longest time interval ($T$) and smallest time interval ($\tau$) of bacteria. Data for the doubling time ($T_{dt}$) are taken from Table 1 and recalculated in seconds.

| Bacteria (t °C) | $\lambda$ (µm) | $T$ (s) | $T_{dt}$ (s) | $\tau$ (s) |
|-----------------|-----------------|---------|--------------|------------|
| 1. Mycoplasma mycoides | 0.0500 | 3.690$\times$10$^2$ | 3.60$\times$10$^3$ | 1.67$\times$10$^{-16}$ |
| 2. Mycoplasma pneumonia | 0.0500 | 1.64$\times$10$^3$ | 4.38$\times$10$^3$ | 1.67$\times$10$^{-17}$ |
| 3. Mycoplasma felis | 0.0555 | 1.267$\times$10$^3$ | 5.22$\times$10$^3$ | 1.84$\times$10$^{-16}$ |
| 4. Mycoplasma hominis | 0.0670 | 5.910$\times$10$^4$ | 3.60$\times$10$^4$ | 1.33$\times$10$^{-15}$ |
| 5. Mycoplasma arthritidis | 0.0500 | 3.690$\times$10$^2$ | 7.20$\times$10$^3$ | 1.67$\times$10$^{-16}$ |
| 6. Ureaplasma urealyticum | 0.0370 | 3.580$\times$10$^2$ | 4.44$\times$10$^4$ | 1.23$\times$10$^{-16}$ |
| 7. Bdelovibrio bacteriovorus | 0.7500 | 4.16$\times$10$^5$ | 1.80$\times$10$^4$ | 6.6$\times$10$^{-17}$ |
| 8. Walbachia melophagi | 0.0594 | 1.55$\times$10$^3$ | 1.8$\times$10$^4$ | 2.0$\times$10$^{-16}$ |
| 9. (a) Staphylococcus aureus | 0.1000 | 1.18$\times$10$^4$ | 7.2$\times$10$^3$ | 3.33$\times$10$^{-16}$ |
| (b) Staphylococcus aureus | 0.1700 | 2.06$\times$10$^4$ | 1.35$\times$10$^4$ | 5.65$\times$10$^{-16}$ |
| 10. (a) Bacillus subtilis | 0.2500 | 1.87$\times$10$^5$ | 1.35$\times$10$^4$ | 7.94$\times$10$^{-16}$ |
| (b) Bacillus subtilis | 0.0830 | 9.05$\times$10$^3$ | 9.0$\times$10$^3$ | 2.76$\times$10$^{-16}$ |
| 11. Escherichia coli | 0.0830 | 9.05$\times$10$^3$ | 9.0$\times$10$^3$ | 2.76$\times$10$^{-16}$ |
| 12. Rickettsia prowazeki | 0.1300 | 1.0$\times$10$^5$ | 2.88$\times$10$^4$ | 1.40$\times$10$^{-15}$ |
| 13. Rickettsia conorii | 0.0630 | 2.35$\times$10$^3$ | 2.88$\times$10$^4$ | 1.40$\times$10$^{-15}$ |
| 14. Thiobacillus thioparus | 0.1250 | 9.6$\times$10$^4$ | 1.2$\times$10$^5$ | 4.16$\times$10$^{-16}$ |
| 15. (a) Spirochaeta lutea | 0.0500 | 2.57$\times$10$^3$ | 1.44$\times$10$^4$ | 0.83$\times$10$^{-16}$ |
| (b) Spirochaeta lutea | 0.1250 | 2.57$\times$10$^3$ | 1.44$\times$10$^4$ | 0.83$\times$10$^{-16}$ |
| 16. (a) Nitrobrocter agilis | 0.0880 | 9.587$\times$10$^3$ | 2.52$\times$10$^4$ | 1.40$\times$10$^{-15}$ |
| (b) Nitrobrocter agilis | 0.1430 | 1.07$\times$10$^3$ | 2.52$\times$10$^4$ | 1.40$\times$10$^{-15}$ |
| 17. Lactobacillus acidophilus | 0.0325 | 9.154$\times$10$^4$ | 2.77$\times$10$^4$ | 3.42$\times$10$^{-15}$ |

Fig. 2. Comparison between the running time ($T$), accuracy ($\tau$), bacterial doubling time ($T_{dt}$) and ATP times ($T_{ATP}$ and $\tau_{ATP}$) of bacterial clock. The times $T_{\text{mean}} = 6.88\times10^4$ s, $T_{dt\text{mean}} = 2.82\times10^5$ s, $\tau_{\text{mean}} = 6.65\times10^{-15}$ s and $\tau_{ATP} = 1.1\times10^{-15}$ s are marked with horizontal continuous line. The time of $T_{ATP} = 1.1\times10^{-14}$ s is marked by dashed line. Standard deviations (±SD) for $T_{\text{mean}}$ (±9.89$\times$10$^4$ s), for $T_{dt\text{mean}}$ (±4.7$\times$10$^5$ s), and for $\tau_{\text{mean}}$ (±7.2$\times$10$^{-16}$ s) are shown.
**Model of Bacteria as Quantum Clock**

The operation of the bacterial cell as a quantum clock can be illustrated with the model represented on Fig. 3. The clock starts to work with the starting growth of the bacteria-mothers. In the end of the growth of the mother cell (after \( T_d \)) appears the bacteria-daughter. There is an understanding that the enzyme machines only received ATP energy for time \( t_{ATP} \) or \( t_{TME} \), but the utilization of the full ATP energy during the time \( t_{ATP} \) of the enzyme reaction (Moltsni et al. 2014; Davies, 2004). In the model we take the mean enzyme reaction-time to be \( t_e \approx 1.0 \times 10^{-16} \) (Metzler, 1977) and one enzyme reaction-time to cause one clockwise movement. For mean total quanta \((N)\) and mean enzyme-time \((t_e)\) of the bacterial clocks can be illustrated with the model represented on Fig. 3.

![Fig. 3. A hypothetic model of bacterial clocks (B_m -bacteria-mother, B_d -bacteria-daughter). Legend: The mean enzyme reaction-time \((t_e)\) determines one clockwise moving. The ATP energy consumption \((E_{ATP})\) from whole bacteria, per one enzyme reaction time \((t_e)\) determines the accuracy of bacterial clock. The doubling time of bacteria \((T_d)\) determines the running time \((T)\) of the clock.](image)

**Discussion**

In our case the calculated smallest time interval ‘\( t \)’ gives the accuracy of the bacterial clock, while the longest time \((T)\) gives the time for which a clock can remain accurate. In our hypothesis we accept that the time parameters of bacteria \((T_{min}, T_{max}, \tau_{TME}, \tau_{ATP})\) are more random in comparison to the genetically determined bacterial mass and size. Because of that, we calculate the bacterial time-characteristics \((T \ and \ \tau)\) as function of bacterial Mass \((M)\), size \((V/S)\) and Planck constant \((h)\), accordingly to Wigner equations, taken as equalities. In our model we compare \( \tau \) with time \( \tau_{ATP} \) for which ATP energy goes to the enzyme molecules and T with doubling time \( T_d \) of bacterial cells, taken as maximum bacterial time-intervals. The received results have showed that the smallest time \( \tau \) corresponds to the real bacterial time-characteristics \( \tau_{ATP} \) i.e., statistically \( \tau_{ATP} \approx \tau_{meas} \). The individual bacterial values for \( \tau \) satisfied the Wigner equation because of \( \tau > \tau_{ATP} \) (Fig. 2). However, more than 70% of calculated values for \( \tau \) were bigger than \( \tau_{ATP} \). On the hand the longest time \( T \) corresponds to real bacterial characteristics (doubling time \( T_d \) i.e., \( T_{min} \approx T_{d \ max} \)). Between the values of calculated longest time \( T \) and experimental data of \( T_d \) exists a relatively good correlation (with \( R = 0.47 \)). This is an additional argument in favor that the bacterial doubling time \( T_d \) represents the calculated longest time \( T \). The individual calculated values for \( T \) satisfied the Wigner equation because of \( T < T_{d \ max} \) (Fig. 2).

The calculated by Equation 10 values of \( T_L \) will be considerably larger than calculated by Equation 6 values of \( T \). For example, the mass of *Mycoplasma mycoides* is \( 1.55 \times 10^{-17} \) kg, the length is \( 0.3 \mu\text{m} \) and the doubling time is \( 3.6 \times 10^{5} \) s. The calculated \( T_L \) is \( 1.3 \times 10^{6} \) s in comparison to the calculated by Equation 6 value of \( T_{VS} = 3.69 \times 10^{7} \) s. In this case the equation from type of \( T_{VS} \approx T_d \) is valid. Thus, in this case the Wigner inequality will be valid and stronger. This example keeps the validity for all bacteria on Table 1. By this fashion (using maximum length of bacterial cell, instead of their volume to surface ratio), the Wigner inequality could be valid more strictly.
We can compare the received results and our model with those of other authors. For example, Zimmerman (1962) point out that a clock of accuracy about 1×10^{-17} (s) and running time 1×10^{-11} (s) would have to weigh up to 1×10^6 D. For 1D = 1.66×10^{-27} (kg) the mass of 10^7 Daltons will be equals to 1.66×10^{-20} kg (mass corresponding to the smallest bacterial mass ~10^{-12}kg). The calculated in our model mean value of clock accuracy $\tau_{\text{mean}} = 6.65\times10^{-16}$s corresponds to the calculated by Pešić and Zimmerman accuracy, but the calculated in our model longest time ($T_{\text{dn mean}}$) differs drastically from Zimmerman’s running time. The calculated mean running time ($T_{\text{mean}}$) is close to the mean bacterial doubling time ($T_{\text{dn mean}}$), but far away from the quantum area. As a compromise, it can be considered that the mean enzyme reaction-time ($t_{E} \sim 10^{-5}$s) falls into the limit between the quantum and classical area of the physics, because this time can be presented as geometric mean between $\tau_{\text{mean}}$ and $T_{\text{dn mean}}$ by the ratio $t_{E} = (\tau_{\text{mean}} \times T_{\text{dn mean}})^{1/2}$. However, it just moves the bacterial clock one step ahead. Only the time of accuracy (in Pešić, Zimmerman and in our models) falls in the quantum area. In conclusion, our calculations confirm the concept of Pešić (1993) that the living bacteria can be regarded as ‘quantum clocks’. In previous publication the author (Atanasov, 2014) presents the problem whether bacteria can be regarded from quantum-mechanical point of view? The answer of this question is more positive than negative, because the basic physical parameters (mass-size-time) of bacteria and the ‘speed of bacterial growth’ satisfied formally the Heisenberg inequalities.

**Conclusion**

In the study we confirmed the hypothesis of Pešić that the bacteria appear to be the smallest quantum clocks in the Nature.

**Ethics**

This article is original and contains unpublished material. The corresponding author confirms that it has no conflicts of interest.

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