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Social Advantage with Mixed Entangled States

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Abstract

It has been extensively shown in past literature that Bayesian game theory and quantum non-locality have strong ties between them. Pure entangled states have been used, in both common and conflict interest games, to gain advantageous payoffs, both at the individual and social level. In this paper, we construct a game for a mixed entangled state such that this state gives higher payoffs than classically possible, both at the individual level and the social level. Also, we use the I-3322 inequality so that states that aren't useful advice for the Bell-CHSH[1] inequality can also be used. Finally, the measurement setting we use is a restricted social welfare strategy (given this particular state).

Keywords

Non-Local Games, Mixed Entangled States, Social-Welfare-Solution

1. Introduction

Quantum theory emerged when most physicists realized that physics at the atomic level could not be completely described by classical mechanics. Planck was the first to propose the notion of "quanta", which was further developed by Einstein. Though Heisenberg and Bohr, the further luminaries of the theory believed in the innate uncertainty in the behavior of atoms, Einstein never accepted it. He fundamentally opposed the *Copenhagen interpretation* of Quantum Mechanics (QM). Thus Einstein-Podolsky-Rosen (EPR) put forward the EPR paradox in their paper in 1935 [1], which claimed QM was incomplete, that is, it did not provide a complete picture of our physical reality.

To resolve this, in their paper, Einstein-Podolsky-Rosen argued for the inclusion of a *Hidden Variable Theory* which would remove all the indeterminism in QM. This led Bohr to publish a paper in the same journal, under the same name,

[1]Bell-Clauser-Horne-Shimony-Holt inequality, 1969.

where he stated that the criterion of physical reality given by EPR contains an essential ambiguity when applied to quantum phenomenon [2]. Hence there continued a debate between Einstein and Bohr regarding the fundamental nature of reality.

In 1964, Bell formulated an inequality [3] which was satisfied by all local realistic theories. Eventually, the quantum violation of Bell's inequality proved that no *local realistic hidden variable Theory* can exist from which QM can be derived. The value by which QM violates a particular Bell inequality is called the *Tsirelson bound* for that particular Bell Inequality. The Tsirelson bound for Bell-CHSH [4] is $2\sqrt{2}$.

Quantum states that violate Bell's inequality are all non-local states (entangled). However, this leads to the question:

Is Bell's inequality sufficient to show non-locality (or entanglement)?

It turns out that Bell's inequality is not sufficient to prove non-locality. The states that violate Bell's inequality are definitely non-local, but there are other states that do not violate a particular Bell inequality but are still non-local. For example, the mixed entangled state in Equation (5) that we consider as the shared resource, does not violate the Bell-CHSH inequality. However, the state is still non-local as can be seen from its violation of the I-3322 inequality. This violation is due to the fact that the I-3322 inequality [5] is inequivalent to any CHSH-like inequality and thus may be used to detect such non-separable states that are not witnessed by any CHSH-like inequality.

By constructing a proof-of-principle non-local game using this inequality and this particular mixed entangled state, we demonstrate that non-pure but non-separable states are also useful as quantum advice (QSWA, defined in Sec. 3.4). By contrast, we know that any two-qubit pure entangled state can be used as QSWA in some non-local game. This result has interesting implications for quantum game theory in general, and quantum cryptographic protocols in particular. The utility of arbitrary (undistillable) bound entangled states in this context, however, remains an open problem that requires further study.

2. Game Theory

Game theory is mathematical modeling of strategic interaction among rational beings, used widely in economics [6], political sciences [7], biological phenomena [8], as well as logic, computer science and psychology [9]. It is the study of human conflict and cooperation, or in other words the study of optimal decision making of different players, each with a set of action having particular payoffs. It is the payoff which decides the preference of an action over another. Von Neumann and Morgenstern [10] were the pioneers of game theory.

Games can be cooperative (common interest) or non-cooperative (conflict interest). Cooperative games include competition between groups whereas non-cooperative game includes analyzing strategies and payoffs of individual players using the concept of Nash equilibrium [11]. In a game, if a player chooses a unique action from a set of available action it is called pure strategy, but if a probability distribution over a set of action is available it is called mixed strategy. Nash proved that in any game with finite number of action for each player there is always a mixed strategy Nash equilibrium. Later the concept of Bayesian games *i.e.*, games of incomplete information was introduced [12] and Aumann proved the existence of correlated equilibria [13] in these games, as opposed to Nash equilibria.

3. Quantum Game Theory

3.1. Non-Locality and Bayesian Game Theory

Non-locality is one of the most counterintuitive aspects of QM. The principle of locality states that an object can be instantaneously affected only by its immediate surroundings and not remote or distant objects. However, quantum theory is not consistent with this and is inherently non-local in nature, unlike the rest of classical physics. For example, two entangled particles placed far apart, can display correlations in simultaneous measurements inexplicable in classical physics. These correlations can not be a result of a signal transfer as that would imply superluminal communication whereas in 1964 Bell [3] showed that they could not arise from predetermined strategies either.

In 2013, Brunner and Linden [14] demonstrated strong links between quantum non-locality and Bayesian game theory. Specifically, they showed that the normal form of a Bayesian game is equivalent to a Bell inequality test scenario. They showed that when the two players in the game share non-local resources such as an entangled pair of quantum particles, they can outperform players using any sort of classical resources. This can happen, for example, when the payoff function of the players corresponds to a Bell inequality, like the CHSH inequality [4], as first discussed by Cheon and Iqbal [15] but also when the payoff function doesn't correspond to any Bell inequality. They showed that more generally, for Bayesian games, QM provides a clear and indisputable advantage over all classical resources.

3.2. Non-Locality in Conflict Interest Games

Brunner and Linden showed that QM indeed provides an advantage over classical resources for all Bayesian games, but the examples they provided were all common interest games (games where it is beneficial for both the players to cooperate rather than oppose each other). In fact, until 2012, all other known non-local games, including the GHZ-Mermin game [16], the Bell-CHSH game [4], and the hidden matching game [17] [18] were all examples of common interest games (mostly, because the average payoff functions for both Alice and Bob were the same).

In 2012, Zu *et al.* [19] proposed a zero-sum (conflict) game where a player using proper quantum strategies could always win. However, for zero-sum games, all strategies are Pareto optimal, meaning, the sum of payoffs is the same for all strategies. In 2015, Anna Pappa *et al.* [20] demonstrated that quantum advice can offer an advantage compared to classical advice even in conflicting interest games. They explicitly constructed an incomplete information game with conflicting interests, where quantum strategies yielded fair equilibria with average payoffs strictly higher than those achievable by classical means, for both the players. Hence, Anna Pappa's work [ibid] was the first where the sum of payoffs was being increased above the classical maximum by using quantum strategies.

3.3. Fair and Unfair Strategies

Classical equilibria can be of two types:

- Fair equilibria, where the average payoffs for both the players are equal;

and

- Unfair equilibria, where the payoffs for the players are unequal.

Up until 2016, most of the games (both common interest and conflicting interest) proposed, dealt with fair equilibria—that is, they showed that quantum fair payoffs surpass classical fair equilibrium payoffs. In 2016, Roy *et al.* [21] showed that quantum strategies can outperform not only fair classical equilibrium strategies but unfair strategies too. They analytically characterized some non-local correlations, that would yield unfair average payoffs strictly higher than the classical ones in Anna Pappa's game.

3.4. Social Welfare Solutions and Pure Entangled States

Until now, we've been concerned only with equilibria for individual players—states where the players can't increase their payoffs further by unilaterally changing their individual strategies. Such equilibria are called correlated equilibria (as opposed to Nash equilibria). Psychological factors indicate that sometimes, instead of focusing solely on their individual payoffs, players may also consider additional social goals—one such idea is the Social Welfare Solution (SWS). In such a strategy, players aim to maximize the sum of their individual payoffs. Out of all the possible quantum strategies, the ones that increase the sum of the payoffs (above the classical value) are called Quantum Social Welfare Solution (QSWS) and the quantum state producing this strategy is called Quantum Social Welfare Advice (QSWA).

In 2019, Banik *et al.* [22] showed that any two-qubit pure entangled state can act as QSWA for some Bayesian game. Hence given any pure entangled state between two qubits, there exists at least one game where this state provides QSWS.

4. Mixed Entangled States and the I-3322 Inequality

A mixed entangled state is a convex combination of pure states that cannot be produced by local operations and classical communication. The decomposition of a mixed entangled state (with density matrix $\rho = \sum_k p_k \rho_1^k \otimes \rho_2^k \otimes \cdots \otimes \rho_n^k$ where $0 < p_k < 1$ are the probabilities and ρ_i^k is the k-th pure state density matrix for the i-th party) into the corresponding pure states (ρ_i^k) is not unique however, and there is no direct way to extend Banik's result [22] to create games where a mixed entangled state can provide QSWS.

The above discussion raises the question:

Can mixed entangled states be used as QSWA for Bayesian games at all?

We answer this question in the affirmative, by explicitly constructing a proof-of-principle Bayesian game, where a mixed entangled state gives higher unfair payoffs and higher social payoffs than classical equilibria.

4.1. The Premise

We consider two players Alice (A) and Bob (B) playing a Bayesian game while being refereed by Charlie. Both Alice and Bob have 3 possible measurement settings ($\{A_1, A_2, A_3\}$ and $\{B_1, B_2, B_3\}$) which result in one of two outcomes {0, 1} each. Charlie asks A and B to implement one of these measurements each (*i.e.* A_i, B_j) and they reply with their respective measurement outcomes (x, y). In this scenario, we define $P(x, y | A_i, B_j)$ to be the probability that when A is asked A_i and B is asked B_j, they reply with x and y as their measurement outcomes, respectively, with $x, y \in \{0,1\}$.

First, we construct the classical game. Here the measurement settings can be thought of as questions asked by Charlie to Alice and Bob, and the measurement outcomes as their answers to the questions.

4.2. The Classical Game

4.2.1. Classical Strategies

A classical strategy means A and B both locally decide their answers to the questions. For each question, A or B can answer either 0 or 1. So for the entire set of 3 questions, there are $2^3 = 8$ different sets of answers. Each such set of answers is called a strategy for that particular player. For example, if A decides to answer 0 to all questions (that is 0 for A_1, 0 for A_2 and 0 for A_3) then her strategy is 000.

We label these strategies $\{g_i\}$ by converting the binary answer sequence (for A_1, A_2, A_3 or B_1, B_2, B_3, in this order) into its decimal equivalent. For example, 000 becomes g_0 and 010 becomes g_2 and so on. The ordered pair of Alice and Bob's individual strategies (g_i^A, g_j^B) called a strategy pair for A and B.

4.2.2. Probability Boxes

The probability box (also called local box) is a table which shows how the strategy relates the questions to the answers. It shows for each question, with what probability a player chooses a particular answer. There is a one-to-one relation between the strategy ordered pair (g_i^A, g_j^B) and the probability box.

Local boxes respect locality, that is the probability that A gives a particular answer to some question is independent of what B is asked and what his response is. For the sake of convenience, a general classical probability box is usually written in the form shown in **Table 1**. $\{C_{ij}, M_i, N_j\}$ are all probabilities and hence $\in \{0, 1\}$.

Row A_iB_j and column xy represents probability of answering (x, y) for the

Table 1. Form of a general probability box.

	OO	$O1$	$1O$	11
A_1B_1	C_{11}	$M_1 - C_{11}$	$N_1 - C_{11}$	$1 - M_1 - N_1 + C_{11}$
A_1B_2	C_{12}	$M_1 - C_{12}$	$N_2 - C_{12}$	$1 - M_1 - N_2 + C_{12}$
A_1B_3	C_{13}	$M_1 - C_{13}$	$N_3 - C_{13}$	$1 - M_1 - N_3 + C_{13}$
A_2B_1	C_{21}	$M_2 - C_{21}$	$N_1 - C_{21}$	$1 - M_2 - N_1 + C_{21}$
A_2B_2	C_{22}	$M_2 - C_{22}$	$N_2 - C_{22}$	$1 - M_2 - N_2 + C_{22}$
A_2B_3	C_{23}	$M_2 - C_{23}$	$N_3 - C_{23}$	$1 - M_2 - N_3 + C_{23}$
A_3B_1	C_{31}	$M_3 - C_{31}$	$N_1 - C_{31}$	$1 - M_3 - N_1 + C_{31}$
A_3B_2	C_{32}	$M_3 - C_{32}$	$N_2 - C_{32}$	$1 - M_3 - N_2 + C_{32}$
A_3B_3	C_{33}	$M_3 - C_{33}$	$N_3 - C_{33}$	$1 - M_3 - N_3 + C_{33}$

question A_iB_j, that is $P(x, y | A_i, B_j)$. It is easy to see that this is a local box, since, for example, the probability that A answers 0 to A_1B_1 is $P(00 | A_1B_1) + P(01 | A_1B_1) = M_1$ which is the same as the probability that A answers 0 to A_1B_2 or A_1B_3, etc. So the probability that A given question A_1 answers 0 is the same independent of what question B is asked.

4.2.3. Utility Boxes

For a particular game, each player chooses one out of these 8 strategies available to them. While the strategy dictates the move or answers that the player gives upon being asked the question, the reward or payoff he gets from that answer is described by the utility box. Given the strategy pair (g_i^A , g_j^B), each player's individual payoffs can be calculated from the utility boxes.

A's answers are listed along the columns and B's along the rows. For a question pair (A_i, B_j), the ordered pair (u_1, u_2) in the row x and column y of the corresponding utility box represents the payoffs A and B get, respectively, on answering with x and y. We designate A's reward as $u_1 = u_A(x, y | A_i, B_j)$ and B's as $u_2 = u_B(x, y | A_i, B_j)$. The utility boxes we use are listed below.

For questions A_1B_1, A_1B_2, A_1B_3

	0	1
0	$\frac{2}{3}$, 1	$-\frac{1}{3}$, 0
1	0, $\frac{1}{3}$	0, $\frac{1}{3}$

For questions A_2B_1 and A_3B_2

	0	1
0	$\frac{1}{2}$, 0	$\frac{1}{2}$, 0
1	$-\frac{1}{2}$, -1	$\frac{1}{2}$, 0

For questions A_2B_3 and A_3B_2

	0	1
0	$-\frac{2}{3}$, $-\frac{1}{3}$	$\frac{1}{3}$, $\frac{2}{3}$
1	$\frac{1}{3}$, $\frac{2}{3}$	$\frac{1}{3}$, $\frac{2}{3}$

For questions A_2B_2

	0	1
0	$\frac{1}{3}, -\frac{2}{3}$	$\frac{1}{3}, \frac{2}{3}$
1	$-\frac{2}{3}, -\frac{1}{3}$	$\frac{1}{3}, \frac{2}{3}$

For questions A_3B_3

	0	1
0	$0, 0$	$-\frac{1}{3}, \frac{1}{3}$
1	$\frac{1}{3}, -\frac{1}{3}$	$0, 0$

4.2.4. Classical Payoffs

For each strategy pair (g_i^A, g_i^B) that Alice and Bob choose, they get a payoff, which can be calculated by using the strategy (probability box) to find the players answer and then using the utility box to find the corresponding payoff. The expected payoffs (F_A, F_B) are then calculated by averaging over all possible questions as follows:

$$F_A = \sum\nolimits_{x,y,i,j} p(i,j) P(x,y \mid A_i, B_j) u_A(x,y,A_i,B_j)$$

$$F_B = \sum\nolimits_{x,y,i,j} p(i,j) P(x,y \mid A_i, B_j) u_B(x,y,A_i,B_j)$$

where, $p(i,j)$ is the probability that the question pair (A_i, B_j) is asked. In our game, Charlie asks Alice and Bob each question pair with equal probability. Then, $p(i,j) = \frac{1}{N^2} \forall (i,j)$ where N is the number of questions. Here, there are 3 questions for each party so $p(i,j) = \frac{1}{9} \forall (i,j)$.

The classical payoffs, using the probability box for $P(x,y \mid A_i, B_j)$ and the utility boxes for u_A and u_B, are then:

$$\begin{aligned} F_A &= \frac{1}{9}\bigg(C_{11} + C_{12} + C_{13} + C_{21} + C_{31} - C_{23} - C_{32} + C_{22} \\ &\quad - M_1 - 2N_1 - N_2 - \frac{M_3}{3} + \frac{N_3}{3} + 2 \bigg) \\ F_B &= \frac{1}{9}\bigg(C_{11} + C_{12} + C_{13} + C_{21} + C_{31} - C_{23} - C_{32} + C_{22} \\ &\quad - M_1 - 2N_1 - N_2 + \frac{M_3}{3} - \frac{N_3}{3} + 3 \bigg) \end{aligned} \tag{1}$$

The C_{ij}, M_i, N_j values ($\in \{0, 1\}$ for classical strategies) are completely determined by the strategy pair (g_i^A, g_j^B). Moreover, since the expressions for F_A and F_B are different, the payoffs are in general unfair.

4.2.5. Classical Equilibria

Since each of the players has a choice of 8 different strategies ($g_0, g_1, \cdots, g_7$), the final payoff box is an 8 × 8 table (see Table 2) of ordered pairs, with the first entry being the payoff for Alice and the second one being the payoff for Bob. A

Table 2. Payoff table.

	g_0	g_1	g_2	g_3	g_4	g_5	g_6	g_7
g_0	6, 9	5, 10	6, 9	**5, 10**	3, 6	2, 7	3, 6	2, 7
g_1	7, 8	**6, 9**	4, 5	3, 6	7, 8	**6, 9**	4, 5	3, 6
g_2	3, 6	−1, 4	**6, 9**	2, 7	3, 6	−1, 4	6, 9	2, 7
g_3	4, 5	0, 3	4, 5	0, 3	**7, 8**	3, 6	**7, 8**	3, 6
g_4	0, 3	2, 7	3, 6	**5, 10**	0, 3	2, 7	3, 6	5, 10
g_5	1, 2	3, 6	1, 2	3, 6	4, 5	**6, 9**	4, 5	**6, 9**
g_6	−3, 0	−4, 1	3, 6	2, 7	0, 3	−1, 4	6, 9	5, 10
g_7	−2, −1	−3, 0	1, 2	0, 3	4, 5	3, 6	7, 8	**6, 9**

factor of $\frac{1}{27}$ has been ignored in Table 2, to keep things cleaner.

The equilibria (all are biased/unfair) have been indicated in bold font. These are the stable states for this game. Also, social welfare solution payoff is $\frac{15}{27}$. Our next task is to check whether a quantum strategy can increase payoffs of the individual parties above the classical values.

4.3. Quantum Game

Now, we devise the means to play this game using a quantum state. In this scenario, the two players share a Mixed Entangled State. They are asked questions A_1, A_2, A_3 and B_1, B_2, B_3 respectively, and they get their answer by performing suitable measurements on the shared state. The objective is to generate a payoff for both players that exceed the classical equilibrium payoffs.

We do this by implanting a quantum inequality in the payoff function so that quantum processes can exceed the upper bound for classical processes and hence produce payoffs higher than all classical payoffs.

4.3.1. The Inequality

We choose the I-3322 inequality. This inequality was discovered in 2003 by Collins and Gisin [5], but little work was done on it, other than finding it's maximal violation value using infinite dimensional quantum systems in 2010 [23].

The important thing about this inequality is that it is inequivalent to the Bell-CHSH inequality. This means that there are states that don't violate Bell-CHSH inequality but violate this.

The inequality is usually represented in the following way:

	−1	0	0
−2	1	1	1
−1	1	1	−1
0	1	−1	0

where the numbers correspond to the coefficients of:

	$P(A_1)$	$P(A_2)$	$P(A_3)$
$P(B_1)$	$P(A_1B_1)$	$P(A_2B_1)$	$P(A_3B_1)$
$P(B_2)$	$P(A_1B_2)$	$P(A_2B_2)$	$P(A_3B_2)$
$P(B_3)$	$P(A_1B_3)$	$P(A_2B_3)$	$P(A_3B_3)$

in the expression. Here, for succinctness, we write $P(00|A_iB_j)$ as $P(A_iB_j)$ and $P(0|A_i)$ as $P(A_i)$.

Rewriting the inequality in our chosen nomenclature, we get

$$\begin{aligned} S = & -\frac{1}{3}P(01|A_1B_1)-\frac{2}{3}P(10|A_1B_1)+\frac{1}{3}P(00|A_1B_2)-\frac{1}{3}P(01|A_1B_2) \\ & -\frac{1}{3}P(10|A_1B_2)+\frac{2}{3}P(00|A_1B_3)-\frac{1}{3}P(01|A_1B_3)+\frac{1}{3}P(00|A_2B_1) \\ & -\frac{2}{3}P(10|A_2B_1)+\frac{2}{3}P(00|A_2B_2)-\frac{1}{3}P(10|A_2B_2)-P(00|A_2B_3) \\ & +\frac{1}{3}P(00|A_3B_1)-\frac{2}{3}P(10|A_3B_1)-\frac{4}{3}P(00|A_3B_2)-\frac{1}{3}P(10|A_3B_2) \end{aligned} \tag{2}$$

After plugging in the variables from the probability box, Equation (2) becomes

$$S = C_{11}+C_{12}+C_{13}+C_{21}+C_{22}-C_{23}+C_{31}-C_{32}-M_1-2N_1-N_2. \tag{3}$$

4.3.2. Maximum Violation of the Inequality

For all classical systems, I-3322 satisfies $S \le 0$. For quantum mechanical systems however, a numerical optimization suggests that the maximum value is 0.25 [5]. The same is suggested by another approach using infinite dimensional quantum systems [23].

The state that produces this maximum value is the maximally entangled Bell state $|\bar{\psi}\rangle$

$$|\bar{\psi}\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right) \tag{4}$$

Choosing appropriate measurements for A and B, gives the value of the inequality

$$S_{|\bar{\psi}\rangle} = 0.25.$$

Also, since $F_A + F_B = \frac{1}{9}(2S+5)$ and this state gives the maximum possible value of S, this state is automatically the SWS for this game.

However, since this inequality is in-equivalent to the Bell-CHSH inequality, there exist states that violate this inequality but not the Bell-CHSH inequality. We choose one such mixed entangled state and corresponding measurements, with the aim to increase the payoffs beyond classical limits.

4.3.3. The Quantum State

The state shared between the A and B is the following mixed entangled state:

$$\rho_{AB} = 0.85|\Phi\rangle\langle\Phi| + 0.15|01\rangle\langle 01|$$

where

$$|\Phi\rangle = \frac{1}{\sqrt{5}}\left(2|00\rangle + |11\rangle\right) \tag{5}$$

The density matrix for the state ρ_{AB} is then:

$$\rho_{AB} = \begin{bmatrix} 0.68 & 0 & 0 & 0.34 \\ 0 & 0.15 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0.34 & 0 & 0 & 0.17 \end{bmatrix}$$

4.3.4. The Measurements

The 6 questions in the classical game have their corresponding measurements for the quantum version. These are all projective measurements, specified by their polar and azimuthal angles (θ, φ). The probabilities for these measurements are calculated by applying the density matrix of the proper eigenvalue of the measurement operator on the density matrix of the quantum state and then taking its trace.

$$A_1 \equiv (\eta, 0),\ A_2 \equiv (-\eta, 0),\ A_3 \equiv \left(-\frac{\pi}{2}, 0\right)$$

$$B_1 \equiv (-\chi, 0),\ B_2 \equiv (\chi, 0),\ B_3 \equiv \left(-\frac{\pi}{2}, 0\right)$$

Such that $\cos\eta = \sqrt{\frac{7}{8}}$ and $\cos\chi = \sqrt{\frac{2}{3}}$.

Applying the measurements, with the appropriate eigenvalues, we find out all the elements of the probability box as follows:

$$M_1 = 0.808687,\ M_2 = 0.808687,\ M_3 = 0.5$$

$$N_1 = 0.646969,\ N_2 = 0.646969,\ N_3 = 0.5$$

$$C_{11} = 0.576785,\ C_{12} = 0.646188,\ C_{13} = 0.464447,$$
$$C_{21} = 0.646188,\ C_{22} = 0.576785,\ C_{23} = 0.344239,$$
$$C_{31} = 0.421634,\ C_{32} = 0.225335,\ C_{33} = 0.08$$

4.3.5. Quantum Payoffs

The quantum payoffs are then calculated using the same formulae as those for classical payoffs. Putting the values in Equation (1), we get:

$$F_A = \frac{6.03858}{27} \text{ and } F_B = \frac{9.03858}{27} \tag{6}$$

The quantum payoff values from Equation (6), that is ($\frac{6.03858}{27}, \frac{9.03858}{27}$) is greater than the classical equilibrium value ($\frac{6}{27}, \frac{9}{27}$).

Also, the quantum social welfare value $\frac{15.0772}{27}$ exceeds that for all classical equilibria ($\frac{15}{27}$).

5. Discussions and Conclusions

We have, hence, constructed a game where a mixed entangled state provides higher individual payoffs than the classical equilibria. The social welfare payoff is also increased beyond the upper limit for the classical scenario. Note that the quantum strategy that we chose generated higher payoffs than one particular classical equilibrium but by modifying the utility boxes, it is possible to dominate any particular classical equilibrium without disrupting the social welfare value, thus preserving the QSWA. It is also possible to increase the social welfare value to its upper limit (strict inequality still holds) for quantum systems, $\frac{16.5}{27}$ by modifying the coefficients of the mixed entangled state. Finally, we point out that given this particular quantum advice from the referee, the measurement settings chosen maximize the Social Welfare Value and thus is a restricted SWS.

However it still remains an open question whether similar to pure entangled states, every mixed entangled state can be used as QSWA for some Bayesian game.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Investigation of Quantum Entanglement through a Trapped Three Level Ion Accompanied with Beyond Lamb-Dicke Regime

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Abstract

In this study, our goal is to obtain the entanglement dynamics of trapped three-level ion interaction two laser beams in beyond Lamb-Dicke parameters. Three values of LDP, $\eta = 0.09$, $\eta = 0.2$ and $\eta = 0.3$ are given. We used the concurrence and the negativity to measure the amount of quantum entanglement created in the system. The interacting trapped ion led to the formation of phonons as a result of the coupling. In two quantum systems (ion-phonons), analytical formulas describing both these measurements are constructed. These formulas and probability coefficients include first order terms of final state vector. We report that long survival time of entanglement can be provided with two quantum measures. Negativity and concurrence maximum values are obtained N = 0.553 and for LDP = 0.3. As a similar, the other two values of LDP are determined and taken into account throughout this paper. For a more detailed understanding of entanglement measurement results, "contour plot" was preferred in Mathematica 8.

Keywords

Entangled State, Trapped Three-Level Ion, Lamb-Dick Parameter, Rabi Frequency, Quantum Measures

1. Introduction

Quantum states as usual are evident in itself with laws in quantum information theory [1]. Entangled states are the proper kind of quantum correlation between two quantum system. Entanglement is an attractive physical phenomenon in which the overlap of two separable states is can be entangled state with photons. The widely read Einstein, Podolsky and Rosen (EPR) paper, contrary to what is known, has actually been published to criticize quantum mechanical laws [2]. In the same year, N. Bohr published a paper [3] with alike this EPR paper. The prominent article presented the entanglement with conversations on quantum theory. For the quantum theory, 1935 was an interesting year. In Erwin Schrödinger's article in Naturwissenschaften introducing "Verschränkung", where he advocated quantum theory [4].

Quantum entanglement has dramatically increased during the last two decades due to the emerging field of quantum information theory [5]. Entanglement is one of important features of quantum theory with no classical analog and quantum computing. Quantum measurement is discussed a local physical process [6]. Nonclassical nature of quantum entanglement has been long recognized [2] [7]. There has been an extensive research in the field of quantum communication which yields a variety of methods to distribute bipartite entanglement. It has reported an applying entanglement created the exchange interaction for many quantum information processing [8]. The maximally entangled states can be modelled physically by the states trapped atomic ions [9] [10] [11]. Trapped ions are between the most attractive implementations of quantum bits for applications in quantum information processing, due to their long coherence times [12]. Ions confined in a linear radio-frequency (Paul) trap are cooled to form a spatial array. Hilbert space of the composite quantum system considered in this paper can be written as

$$C^{d} = C^{d_{ION}} \otimes C^{d_{p}} \tag{1}$$

where $d_{ION} = 3$ and $d_{p} = 4$ represent the dimensions at three-level ion and photons, respectively. We characterize quantum correlations using concurrence (C) [13], negativity (N) [14], and quantum entropy [11] [15] [16] for time dependent interaction of a three-level trapped ion with two laser beams. Trapped ions systems are important for the entangled states Works. Quantum entanglement measurements are used to determine any known state is separable or entangled. Therefore, C and N are offered for pure states [17] [18]. N and C are an entanglement measure that a useful characterization in quantum information, commonly in ionic system. Product base and entangled base are shown generalization of Schmidt coefficients.

The deep Lamb-Dicke regime (LDR) described with LDP of small, $\eta \ll 1$. LD limit is not accordingly established with common experiments [19]. Such a way experiments act in named as beyond LDR here $\eta < 1$, for example $\eta = 0.2$ [20], such as this work. Entanglement of qutrit states [10] are testified by a quantum system for lower order terms of density matrix.

We report analytical results of quantum entanglement for system via N and C for the LDR and 12-Dimensional (D) of Hilbert space. We focus the quantum correllations in N *and* C *[10]* [11] [16] with respect to the total and the reduced density matrix. With respect to Ref. [9], we illustrated these evolutions of N for trapped ion-phonons system.

The rest of the study is coordinated as follows. Section 2 discusses growth for two unentangled qubits and analitical solutions in the quantum system. Section 3 describes how to obtain highly *N* and *C* of two quantum systems by the LDR. The results and comments are given in Section 4.

2. A Quantum Solution of Ion-Phonons System and Its Theory

For section 2, flow chart is:

- In this section, the Hamiltonian and its dynamics are given between Equations (1)-(5).
- In Λ configuration, U transformation matrix processes evolved in Equations (6)-(11).
- The initial state of the system has written by Equations (12)-(22).
- Equation (3) is the final state of the ion-phonons system.
- In Equations (24)-(32), the probability applitudes are given.

We propose a trapped atomic ion interacting with two laser beams. In this system, the Hilbert space dimension is 12. The quantum dynamics of trapped ion-phonons system is emerged by previous investigation [9] [21] [22]. The Hamiltonian of two quantum systems is $H_{total} = H_{Ion} + H_1 + H_2$, and H_{Ion} indicates Hamiltonian of system ($\hbar = 1$):

$$H_{Ion} = \omega_g |g\rangle\langle g| + \omega_r |r\rangle\langle r| + \omega_e |e\rangle\langle e| + \frac{p_x^2}{2m} + \frac{1}{2} m\upsilon^2 x_{Ion}^2 . \tag{2}$$

The e-level energy is $\omega_e = 0$, r-level is ω_r, and g-level is ω_g. The reason for ω_e to be zero is the following: As can be seen in Equation (12), the excited level $|e\rangle$ is removed in the first quantum state. Here H_1 and H_2 are Hamiltonians of these interactions for *excited-ground* and *excited-raman*:

$$H_{e-g} = H_1 = \frac{\Omega}{2} e^{i(k_1 x_{Ion} - \omega t)} |e\rangle\langle g| + h.c. \tag{3}$$

$$H_{e-r} = H_2 = \frac{\Omega}{2} e^{i(-k_2 x_{Ion} - \omega t)} |e\rangle\langle r| + h.c. \tag{4}$$

where $\hbar = 1$, p_x and x_{Ion} are momentum and the *x*-component of position of ion center of mass movement. The movement of ion in the system is along the *x*-axis (one-D). Atomic levels are shown: $|e\rangle \rightarrow$ trapped ion excited level, $|r\rangle \rightarrow$ raman level, and $|g\rangle \rightarrow$ ground level. Trapped ionmass center is given with standard harmonic-oscillator of H_{ion} in $p_x = i\sqrt{\frac{1}{2} m\upsilon} \left(a^+ - a\right)$ and $x_{Ion} = \sqrt{\frac{1}{2m\upsilon}} \left(a + a^+\right)$. Here, *a* is annihilation operator and a^+ creation operator for two laser beams. Laser frequencies are ω_1 and ω_2, and Rabi frequency is Ω. Trapped ion-phonons total Hamiltonian is written ($\hbar = 1$):

$$H = \left(\frac{\Omega}{2} e^{i\eta\left(a^+ + a\right)} |e\rangle\langle g| + \upsilon a^+ a - \delta |e\rangle\langle e| + \frac{\Omega}{2} e^{-i\eta\left(a + a^+\right)} |e\rangle\langle r| \right) + h.c., \tag{5}$$

here, LDP is $\eta = k/2m\upsilon$, υ is trap frequency of harmonic, and delta function is $\delta = \upsilon\eta^2$. We have taken the base vectors as follow:

$$|e\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \ |r\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \ |g\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \tag{6}$$

In this study, important transformed Hamiltonian is $\tilde{H} = U^{+}HU$. Hamiltonian in Equation (5) is found after transmission action. Λ model is given by a cascade Ξ scheme in two phonons. Ion-two phonons system was covered by unitary transformation. Matrix of transformation, namely U is performed [21],

$$U = \frac{1}{2}\begin{pmatrix} 0 & \sqrt{2} & \sqrt{2} \\ -\sqrt{2}B[\eta] & B[\eta] & -B[\eta] \\ \sqrt{2}B[-\eta] & B[-\eta] & -B[-\eta] \end{pmatrix}. \tag{7}$$

Here displacement operators of Glauber, $B(\eta) = e^{\left(i\eta\left(a+a^{+}\right)\right)}$, $B(-\eta) = e^{\left(-i\eta\left(a+a^{+}\right)\right)}$ are achieved. $\tilde{H}$ is performed $\tilde{H} = \tilde{H}_0 + \tilde{V}$, here

$$\tilde{H}_0 = \upsilon\left(|r\rangle\langle r| - |g\rangle\langle g|\right) + \upsilon\eta^2 + \upsilon a^{+}a \tag{8}$$

$$\tilde{V} = -i\frac{\sqrt{2}\delta\eta}{2}\left(a^{+}|e\rangle\langle r| - a^{+}|e\rangle\langle g| + h.c.\right). \tag{9}$$

In our system, the LDR is performed between the values 0.09 and 0.3 of LDP. By using unitary transformation method [21], an initial state $|\psi(0)\rangle$ is written in following form

$$|\psi(t)\rangle = U_0^{+}Ue^{-it\tilde{H}_0}K(t)U^{+}|\psi(0)\rangle, \tag{10}$$

where $K(t)$ is typical vector for time-independent Hamiltonian; $e^{\left(-it\tilde{H}_0\right)}$ is the exponencial function, and $U_0 = \exp\left(-i\omega t|e\rangle\langle e|\right)$ is the transformation matrix [21]. Trapped ion two phonon states system acts for Λ scheme. The propagator is performed

$$K(t) = \frac{1}{2}\begin{pmatrix} Cos(\Lambda t) & -\varepsilon Sa^{+} & -\varepsilon Sa \\ \varepsilon aS & 1+\varepsilon^2 aGa^{+} & \varepsilon^2 aGa \\ \varepsilon a^{+}S & \varepsilon^2 a^{+}Ga^{+} & 1+\varepsilon^2 a^{+}Ga \end{pmatrix}, \tag{11}$$

here $\varepsilon = \upsilon\eta/\sqrt{2}$, $\Lambda = \varepsilon\sqrt{2a^{+}a+1}$, $G = \frac{\cos(\Lambda t)}{\Lambda^2}$ and $S = \frac{\sin(\Lambda t)}{\Lambda}$. We take $\upsilon = 10^6\,\text{Hz}$ and $\omega_{eg} = 5\times10^{14}\,\text{Hz}$ for frequencies. In the system, we take $a = 1$ and $b = 0.005$. Normalization condition of ion is certainly $\left[\frac{1}{\sqrt{2}}\right]^2 + \left[-\frac{1}{\sqrt{2}}\right]^2 = 1$, and normalization condition of two phonons is $\|a\|^2 + \|b\|^2 = |1|^2 + |0.005|^5 \cong 1$, approximately. So, the earliest of trapped ion-phonon states system is given as

$$|\psi(0)\rangle = \frac{1}{\sqrt{2}}\left[|g\rangle - |r\rangle\right] \otimes \left(a|0\rangle + b|1\rangle\right), \tag{12}$$

here, the phonon levels are $\langle 0| = (1,0)$, and $\langle 1| = (0,1)$. a and b are the probability amplitudes of the first and the second phonon. New equation for ion-two phonons is performed as

$$\left|\psi(0)\right\rangle = \frac{1}{\sqrt{2}}\left[\left|g\right\rangle - \left|r\right\rangle\right] \otimes \left(\sum_{n=0}^{\infty} F_n(b)\left|n\right\rangle\right). \tag{13}$$

It is used by η^0 and η^1 are zero and first-order indication of LDP, respectively. Beside, both of them, η^2 and η^3 are ignored. Ion-phonons system is evolved to an initial unentangled state,

$$\left|\psi K(t)\right\rangle = \left|\tilde{\psi}(0)\right\rangle = U^{+}\left|\psi(0)\right\rangle = \sum_{\sigma,m} N_{\sigma,m}(t)\left|\sigma,m\right\rangle. \tag{14}$$

In Equation (12), our system is produced in respect of $\sum_{\sigma,m} N_{\sigma,m}(t)\left|\sigma,m\right\rangle$. As a result of advanced mathematical transformations between Equation (10)-(14), 12 of significiant coefficients are

$$scN_{e0}(t) = \left[\cos\left(\sqrt{\frac{1}{2}}t\right) + \frac{\eta i}{\sqrt{2}}\sin\left(\sqrt{\frac{1}{2}}t\right)\right]\exp\left[-ti/\eta\right] \tag{15}$$

$$scN_{e1}(t) = b\cos\left(\sqrt{\frac{3}{2}}t\right)\exp\left[-ti/\eta\right] \tag{16}$$

$$scN_{e2}(t) = -\frac{\eta i}{\sqrt{5}}\sin\left(\sqrt{\frac{5}{2}}t\right)\exp\left[-2ti/\eta\right] \tag{17}$$

$$scN_{r0}(t) = \frac{b}{\sqrt{3}}\sin\left(\sqrt{\frac{3}{2}}t\right)\exp\left[-ti/\eta\right] \tag{18}$$

$$scN_{r1}(t) = \frac{\eta i}{\sqrt{2}}\left[\frac{3}{2} + \frac{2}{5}\cos\left(\sqrt{\frac{5}{2}}t\right)\right]\exp\left[-2ti/\eta\right] \tag{19}$$

$$scN_{g1}(t) = \left[\sin\left(\sqrt{\frac{1}{2}}t\right) - \frac{\eta i}{\sqrt{2}}\cos\left(\sqrt{\frac{1}{2}}t\right)\right]\exp\left[-ti/\eta\right] \tag{20}$$

$$scN_{g2}(t) = b\sqrt{\frac{2}{3}}\sin\left(\sqrt{\frac{3}{2}}t\right)\exp\left[-ti/\eta\right] \tag{21}$$

$$scN_{g3}(t) = -\frac{\sqrt{3}}{5}\eta i\left[1 - \cos\left(\sqrt{\frac{5}{2}}t\right)\right]\exp\left[-2ti/\eta\right] \tag{22}$$

and four of significiant coefficients are zero:
$scN_{e3}(t) = scN_{r2}(t) = scN_{r3}(t) = scN_{g0}(t) = 0$. For Equations from (15) to (22), index σ is positioned in the states of atomic (g,r,e), index m is positioned by vibrational numbers $(0,1,2,3)$. Vibrational phonon states are located by a Hilbert 4D-space $H_{phonons}$ and subsystem of trapped ion-phonons is located in a Hilbert 3D-space H_{Ion}. Thus, two quantum systems are in Hilbert 12D-space. Here, t is dimensionless and scaled with $\upsilon\eta$. What does $\upsilon\eta$ dimensionless mean? Accordingly in **Figure 1**, time 1 equals to 5 ms (mikrosecond). The mathematical calculation is as follows; for $\eta = 0.2$, $\upsilon\eta = 0.2\times10^{6}$, $\frac{1}{\upsilon\eta} = 5\times10^{-6} = 5$ ms. The state vector is

$$\left|\psi_{final}(t)\right\rangle = \sum_{m=0}^{3}\left(A_m(t)\left|e,m\right\rangle + B_m(t)\left|r,m\right\rangle + C_m(t)\left|g,m\right\rangle\right). \tag{23}$$

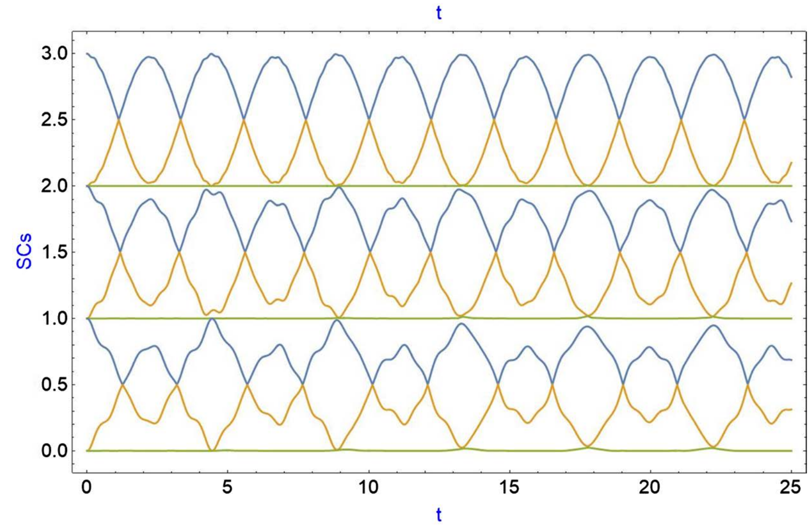

Figure 1. The time dependence of Schmidt coefficients, μ_1, μ_2 and μ_3 for three LDP. Upper, middle and lower curves are for three LDP. The third SC, μ_3 is green and small. Therefore, there are 9 functions in the figure. *t* is dimensionless scaled by $\upsilon\eta$. The earliest state of trapped ion and two phonons system is $\psi(0) = \frac{1}{\sqrt{2}}(|g\rangle - |r\rangle) \otimes (a|0\rangle - b|1\rangle)$ for $a = 1$, $b = 0.005$. These coupling parameters are written for $\upsilon = 1\,\text{MHz}$ and $\omega_{eg} = 5 \times 10^{14}\,\text{Hz}$.

The coefficients $A_m(t), B_m(t)$ and $C_m(t)$ are shown by state vector amplitudes of Λ and Ξ models. 12 of the probability amplitudes of the vector are

$$A_m(t) = \frac{1}{\sqrt{2}} e^{-i\omega t/\upsilon\eta} \left[N_{rm}(t) + N_{gm}(t) \right], (m = 0,1,2,3), \quad (24)$$

$$B_0(t) = -\frac{1}{\sqrt{2}} N_{e0}(t) + \frac{1}{2} N_{r0}(t) - \frac{i\eta}{2} N_{g1}(t) \quad (25)$$

$$B_1(t) = -\frac{i\eta}{\sqrt{2}} N_{e0}(t) - \frac{1}{2} N_{r1}(t) + \frac{1}{2} N_{r1}(t) - \frac{1}{2} N_{g1}(t) \quad (26)$$

$$B_2(t) = -\frac{1}{\sqrt{2}} N_{e2}(t) - \frac{i\eta}{\sqrt{2}} N_{g1}(t) - \frac{1}{2} N_{g2}(t) \quad (27)$$

$$B_3(t) = -\frac{1}{2} N_{g3}(t) \quad (28)$$

$$C_0(t) = \frac{1}{\sqrt{2}} N_{e0}(t) + \frac{1}{2} N_{r0}(t) + \frac{i\eta}{2} N_{g1}(t) \quad (29)$$

$$C_1(t) = -\frac{i\eta}{\sqrt{2}} N_{e0}(t) + \frac{1}{2} N_{r1}(t) + \frac{1}{2} N_{r1}(t) - \frac{1}{2} N_{g1}(t) \quad (30)$$

$$C_2(t) = \frac{1}{\sqrt{2}} N_{e2}(t) + \frac{i\eta}{\sqrt{2}} N_{g1}(t) - \frac{1}{2} N_{g2}(t) \quad (31)$$

$$C_3(t) = -\frac{1}{2} N_{g3}(t) \quad (32)$$

here ω_{eg} is frequency e-g levels and $\omega = \omega_{eg} - \eta^2 \upsilon$ for Equation (24). *i* is complex number, and i is ion index.

We plotted N and C of two quantum systems as $l \otimes l'(l \leq l')$ in **Figures 2-7**

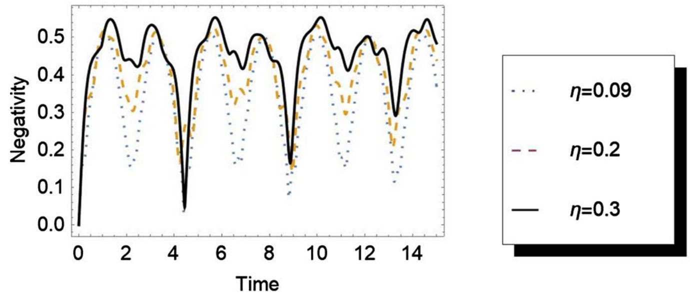

Figure 2. The time dependence of negativity, for three $\eta = 0.09$, $\eta = 0.2$ and $\eta = 0.3$. t is dimensionless and scaled with $\upsilon\eta$, other assumptions parameters are the same as **Figure 1** in the system.

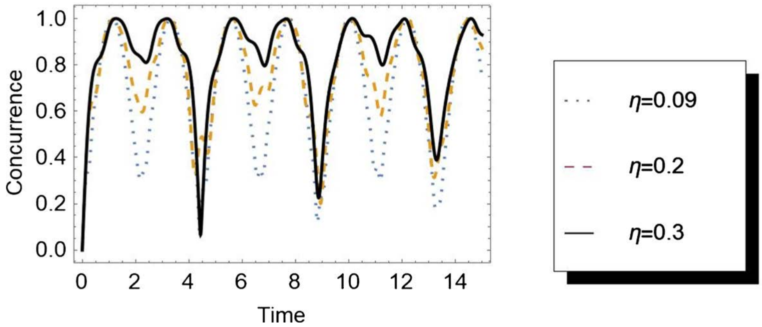

Figure 3. The time dependence of concurrence, for three η. Other assumptions parameters are the same as **Figure 1** in the system.

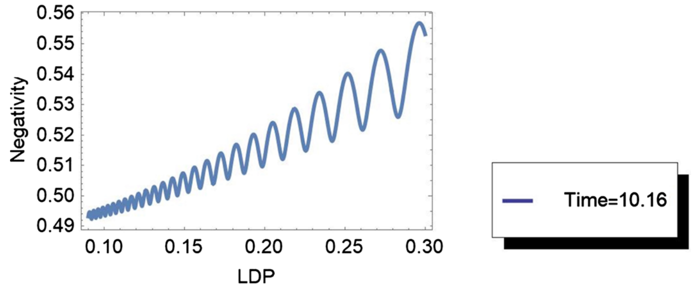

Figure 4. The LDP evolution of N is given $t = 10.16$ s. Other assumptions parameters are the same as **Figure 1** in the system.

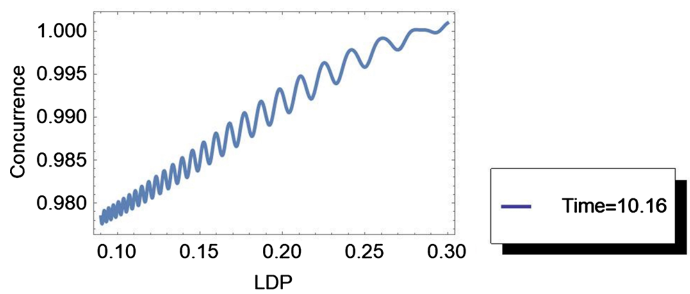

Figure 5. The LDP evolution of C is given $t = 10.16$ s. Other assumptions parameters are the same as **Figure 1** in the system.

and Table 1. We found that final state vector $\left|\psi_{final}(t)\right\rangle$ is superposition of twelve function in Equations (24)-(32).

3. Two Measurements, Beyond LDR and Discussion

Hilbert spaces are $l=4$ for two-phonons, $l'=3$ for ion. It is used a simplified density matrix $\rho_{ion}=Tr_{phonon}\left(\rho_{ion-p}\right)$ by Equation (33). Fully density matrix ρ_{ion-p} is performed with 12×12 matrix with respect to the bases $\left|i,p\right\rangle$. With tracing, 3×3 -simplified density matrix, ρ_{ion} is performed

$$\rho_{ion}=Tr_p\left(\rho_{i-p}\right)=\begin{pmatrix} Tr|e\rangle\langle e| & Tr|e\rangle\langle r| & Tr|e\rangle\langle g| \\ Tr|r\rangle\langle e| & Tr|r\rangle\langle r| & Tr|r\rangle\langle g| \\ Tr|g\rangle\langle e| & Tr|g\rangle\langle r| & Tr|g\rangle\langle g| \end{pmatrix} \tag{33}$$

where diagonal terms, $|e\rangle\langle e|$, $|r\rangle\langle r|$ and $|g\rangle\langle g|$ are a 4×4 -matrix. For help to Equation (32), fully density matrix of two quantum system is written as:

$$\rho_{ion-phonon}=\left(|Z\rangle\langle Z|\right) \tag{34}$$

where $|Z\rangle\langle Z|$ is a 12×12 -square matrix and Hilbert 12-space in qauntum mechanic. The initial state in second section derive in Hilbert 12-space $H=H_i\otimes H_p$. In state vector $\left|\psi(t)\right\rangle$, fully density matrix of system is given by $\rho_{ion-phonon}=\left|\psi(t)\right\rangle\left\langle\psi(t)\right|=|Z\rangle\langle Z|$ in Equation (33). Negativity is first reported in literature as a quantum entanglement measurement in [20].

In this part, we examine if the state is entangled how much quantum entanglement it involves. They are analyzed quantum correlations with concurrence and negativity [17] [23]. The quantum state ψ of a system such as X and Y, with dimensions k and k', can be given

$$|\psi\rangle=\sum_j\sqrt{\mu_j}\left|x_j\right\rangle\left|y_j\right\rangle \tag{35}$$

where $\sqrt{\mu_j},(j=1,\cdots,k)$ are Schmidt coefficients abbreviated as SCs, x_j and y_j are orthogonal basis in H_X and H_Y [23]. We have given by Schmidt form for wave function.

Therefore, three SCs are the three eigenvalues of the matrix in Equation (33), μ_j [23]. Their time dependence is illustrated in Figure 1. Upper two curves are μ_1 and μ_2, while the lower curve, μ_3 is the third SCs for $\eta=0.09$, $\eta=0.2$ and $\eta=0.3$. There are two ways to quantify the quantum entanglement. We work the entanglement of the solutions of our system by calculating negativity and concurrence.

Negativity of any quantum system is written as [23]

$$N\left(|\psi\rangle\right)=\frac{2}{k-1}\left(\sum_{i<j}\sqrt{\mu_i}\sqrt{\mu_j}\right) \tag{36}$$

$$N\left(|\psi\rangle\right)=\frac{2}{3-1}\left(\sqrt{\mu_1}\sqrt{\mu_2}+\sqrt{\mu_1}\sqrt{\mu_3}+\sqrt{\mu_2}\sqrt{\mu_3}\right) \tag{37}$$

Concurrence is developed as a quantum entanglement measurement for bipartite system of two qubits [13] [24]. The concurrence of bipartite system is given by [13] [24]

$$C(|\psi\rangle) = 2\left(\sum_{i<j}\sqrt{\mu_i\mu_j}\right) \quad (38)$$

$$C(|\psi\rangle) = 2\left(\sqrt{\mu_1\mu_2} + \sqrt{\mu_1\mu_3} + \sqrt{\mu_2\mu_3}\right) \quad (39)$$

As shown in **Figures 2-5**, LDPs are taken between 0.09 and 0.30. It is understood that taking these adjustable values of LDP is an appropriate choice, because the N and C values have seen with the maximums. This leads to higher dimensional entanglement with η. In **Figure 2** & **Figure 3**, time evolution of N and C is illustrated by $\eta = 0.09$, $\eta = 0.2$ and $\eta = 0.3$. We have obtained high amount of entanglement for three values of LDP.

We reported entanglement via negativity in the LDR discretely from other papers [9] [17]. The values of N and C in one ideal times are shown with **Table 1**. In **Figures 2-7**, a maximum value of N is reported $N = 0.553$ for $\eta = 0.3$ in **Table 1**. A maximum value of C is reported $C = 1.000$ for $\eta = 0.3$ in **Table 1**. The three values of η are determined and taken into account throughout this study. In literature, we did not see that it has been worked with the value 0.09. We explain quantum dynamics of N and C according to time in **Figures 2-7**. The results of our former studies [9] [10] [17] [18] are in similar in **Figure 3** & **Figure 4**. N, C and E, which are the other advanced measurements defining entanglement motion, have been worked out in literature [7] [11] [18] [19] [20].

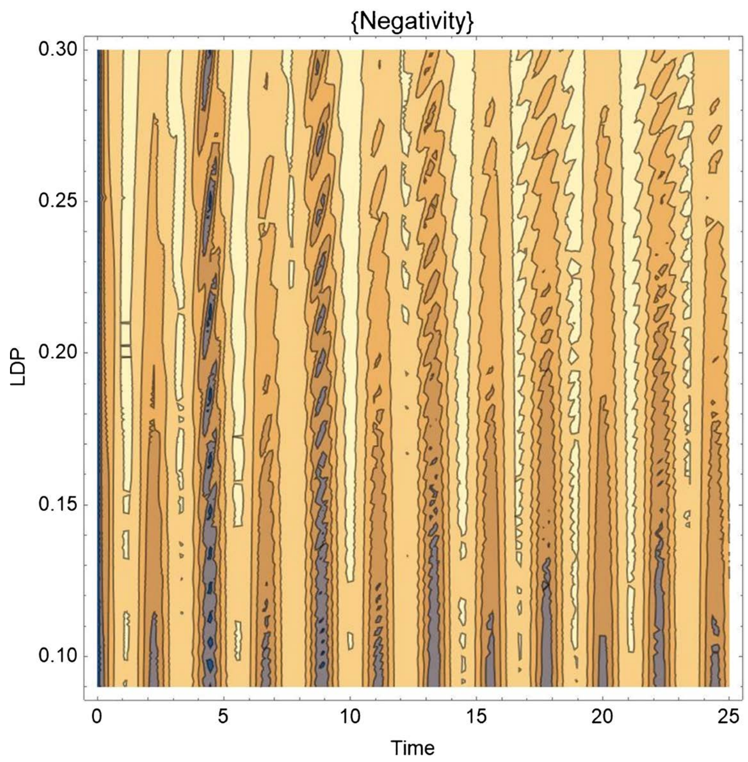

Figure 6. Contour plot of negativity for scaled time change of LDP to 0.3 from 0.09. Color scale from black to orange equals to 0.0 - 1.0. Other assumptions parameters are the same as **Figure 1** in the system.

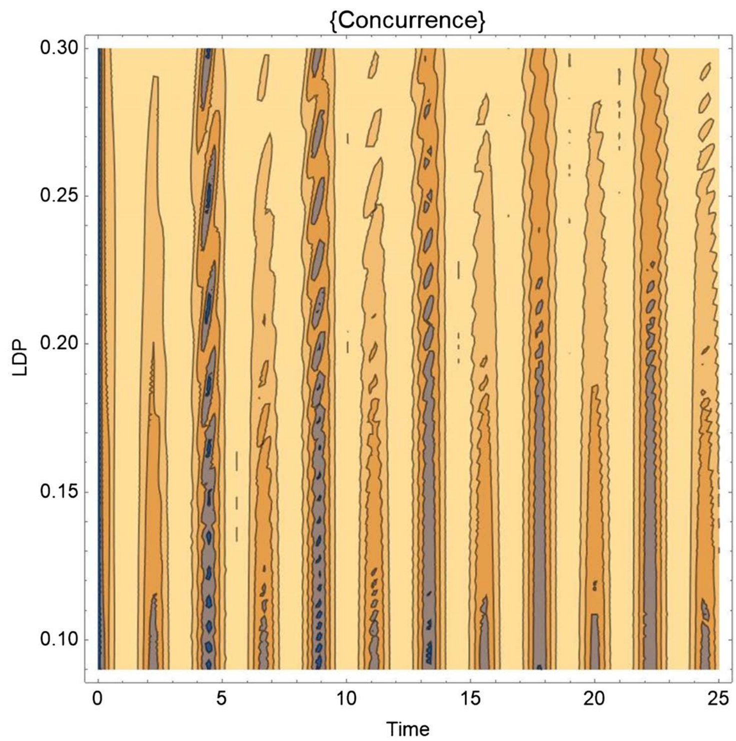

Figure 7. Contour plot of concurrence for scaled time change of LDP to 0.3 from 0.09. Color scale from black to orange equals to 0.0 - 1.0. Other assumptions parameters are the same as **Figure 1** in the system.

Table 1. Six values of negativity and concurrence within one ideal times, t = 10.16 ms or t = 10.16 scaled time, with respect to **Figure 2** and **Figure 3**.

	$\eta = 0.09$	$\eta = 0.2$	$\eta = 0.3$
Negativity, t = 10.16 ms, Figure 2	0.493	0.512	0.553
Concurrence, t = 10.16 ms, Figure 3	0.978	0.992	1.000

We show the quantum correlations with N and C for coupling parameters. We found seperate dynamic features in N in reaction to increasing η. In **Figure 2**, N oscillates between the values of minimum $N = 0$ and highest rate $N = 0.553$ at $t = 10.16$ ms for $\eta = 0.3$. The variations between the maximum and the minimum values of negativity are regular with time. In **Figure 3**, C oscillates between the values of minimum $C = 0$ and highest rate $C = 1.000$ at $t = 10.16$ ms for $\eta = 0.3$. The presence of long lived entanglement in trapped ion and phonons system has been recognized by **Figure 6** & **Figure 7**. We explore with N *and* C that measurement degrees have a flash crop entangled state up in parallel to raising η and this is in comparison to the previous observations [14] [15] [16] [17] [25]. Similar quantum correlations exist between the N and the C: see **Figure 6** & **Figure 7**. The color domain is from White to orange. The lower N and C obtain the darker colored domains. However, the system is disentangled some scaled times in **Figure 6** & **Figure 7**. The existence of quantum entanglement is shown by entropy calculations in subatomic particles such as electron, proton and quark [26]. It is investigated the dynamical and stationary properties of the entanglement entropy after a quench from initial states [27]. The entanglament between measured qubit and memory qubit has been inspected via von Neumann entropy [28]. Quantum entanglement has demonstrated with certain statement in time-dependent fifteen-dimensional Hilbert space [29]. Quantum linearity is theoretically characterized by the second order terms of the LDP [30].

4. Conclusions

We concentrated on quantum entanglement of two quantum systems in the Hilbert 12-space. We investigate the negativity through the definition of variance LDR. Some physical correlations have been that we measure N and C. Our analysis has discovered maximally entangled state. The family is equal to a group of quantum measurements. To more detailed understanding of entanglement measurement results N and C, "contour plot" was preferred in Mathematica 8 in **Figure 6** & **Figure 7**.

These plots are obtained by N and C with quantum corrections. Entanglement is compared and is analyzed by two quantum measures which are N *and* C. Quantum correlations and interactions between ion and two phonons are investigated. Because, the discussion on physical properties of trapped ion-two phonos interaction is an important subject for quantum information.

The main contribution and novelty of my work has been explained with concluding remarks shown below:

- In our system, quantum entanglement is shown to have the capacity and degree of N and C are $N = 0.553$, $C = 1.000$;
- N bases on three different LDPs;
- This extracts that such entanglement is connected with η. We achieved long-lived entanglement in LDR;
- Maximally entangled states as presented by means of ion-two phonons system can be important for researchers with trapped ions;
- Extending the life time can be succeeded by using Rabi frequencies and η. This study and similar studies based on quantum measurement will lead to a better understanding of quantum physics and quantum entanglement.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Quantum Theory and Its Effects on Novel Corona-Virus

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Abstract

Emerging infectious viral diseases are a major threat to humankind on earth, containing emerging and re-emerging pathogenic physiognomies has raised great public health concern. This study aimed at investigating the global prevalence, biological and clinical characteristics of novel Corona-virus, Wuhan China (2019-nCoV), Severe Acute Respiratory Syndrome Corona-virus (SARS-CoV), and Middle East Respiratory Syndrome Corona-virus (MERS-CoV) infection outbreaks [1]. Currently, novel Corona-virus disease COVID-2019 is already pandemic and causing havoc throughout the world. Scientific community is still struggling to come out with concrete therapeutic measures against this disease and development of its vaccine is far off from sight in the immediate near future. However, humanity will be put to such pressures very often in the near future and given the present circumstances, what we can expect from the scientific world now? I think QIT (Quantum Information Theory) has an answer to this question. One of the very basic mechanisms that every infectious virus follows to infect is the entry of the virus through cell surface receptors, engulfing, un-coating of viral genome and its transcription to form multiple copies and translation to form viral proteins and coating of viral genome to form multiple copies of the viral particles and then of course the cell bursting to infect other cells. This very basic mechanism does not occur randomly but through a regulated and more dynamic process which we may call coding and decoding of information through reduction in error or noise.

Keywords

COVID-19, Corona-Virus, QIT, SARS-CoV, Iobits, Neobits

1. Introduction

Lots of discoveries have taken place in scientific world and among them, the virus is one of the significant ones however it appears the smallest. A virus, according to Wikipedia Encyclopedia, is a submicroscopic infectious agent that replicates only inside the living cells of an organism. Viruses can infect all types of life forms, from animals and plants to microorganisms, including bacteria and archaea. Now the question is even in the least possible form, its work is beyond the imagination. It is hard to understand the nature of virus, its configuration and the cause of manifestation is an ordeal and even dreadful. Although, bacteria are the tiniest living organisms found yet but this virus is even tinier and also found in bacteria's [2]. Now the question is even in the tiniest form, how does it exist and what is the mode of manifestation of this virus? Even though there are different types of viruses in the world, this particular one has to be watched very keenly and to study its structure we need to go through microscopic study for which we use electron microscope or electron X-ray techniques and hence, we learn that this living organism works exactly like the others *i.e.* its structure is like a bacteria composing protein and lipid membranes and DNA/RNA which are also found in different shapes and sizes. Now our point is what makes this organism the tiniest [3]?

Scientifically, it has been proven that it contains RNA which works like a code and acts as a source in its formation. In other words, it basically forms from the RNA. But the point is how the RNA actually initiates when later acquires mass and takes the shape of virus [4]. After that, this virus works in two ways initially, in recessive mode and next, in dominant mode *i.e.* this virus keeps on forming an unmatched track and at the same time does its work. The other virus which is primarily in the recessive mode but also looks for the host and then works as the dominant factor *i.e.* it looks for the target to complete its task [5]. But the question is that, how does RNA which is the basic source of its creation, build? To understand this, one has to take aid of quantum information theory that helps in understanding the internal information of the RNA, its configuration and its mode of manifestation. The internal information of the RNA is extremely different from the laws which are identified and acknowledged, it has its own laws and mechanisms that play a key role in acquiring mass wherein super energy mechanism/super time mechanism and super dimensional mechanism are amazing. After interpreting these three laws, let's know how super energy that is in the non-baryonic form with the help of super time and super dimensional mechanism converts into baryonic form? Until, these three laws aren't cognized, formation of this virus won't be grasped.

2. Quantum Information Theory

It is such information which plays an important role in formation of matter that actually is an energy and later with other formulas like super energy, super time and super dimension concepts, changes from non-existing form/non-baryonic form to existing form [6]. This information is actually in hidden geometrical form which we need to understand e.g. it is necessary that every matter contains some information it is because of this information, the matter exists. We have also framed a mathematical equation for this which actually works same as the mechanism found inside the matter at micro level and it has the same functions like the hereditary information has, at the micro level. Since, it is in non-existing form but on quantum level, we can form a quantum information equation that helps in the formation of hereditary information. As we know, hereditary information contains codes which internally are of different charges or have a dual nature. They work as small bits which are linked to each other in order to make a larger bit which has been named as cubit or we can also claim that information is formed on the basis of the smaller bits. These bits of different nature combine to form a sort of pattern *i.e.* the equation that we call as Nano-bit and Iobit means iobit-1 and iobit-2 forms Nano-bit and these Nano-bits later form the precursor of positive and negative charge to make unique cubit. Similarly the other iobits also form different types of Nano-bits and later these Nano-bits combine to form a cubit which acquires a unique charge and this charge later can be differentiated into plus and minus. Now the question is what this plus and minus actually is? This is also a different mechanism which we can understand from super energy concept, super time and super dimension concept and it works like lock and key methodology and it later interacts with the bit of a particular configuration and this method continues till the matter is formed to which we assign different names e.g. plus means positive charge and minus means negative charge, sometime it may also have dual nature. This can be understood by a configuration or geometrical structural information.

3. QIT and Its Role

Actually, the quantum information which is present in it also carries the shape of its manifestation or we can say that quantum information becomes the source of its designing which later takes a geometrical shape [7]. Even though it is present in geometrical information, but it is in non-baryonic/non-existing form initially and later converts into baryonic form. It means that if we will talk about the world of particles, these particles play an important role in the formation of a structure but along with its structure it also has a particular design/pattern which is present in these quantum information bits and play vital role in the designing of the structure or we can say that in any living or non-living matter there is a particular code for its structure [8]. The plant right from its first particle *i.e.* nucleic code till it gets developed into a complete plant, is controlled by genetic code and the hereditary of this plant works through the quantum information which means that the structure/manifestation of all the living organisms/matter is present in their codes and its configuration is hidden in its information.

4. Statistical Analysis

Whenever, the error or noise becomes more absurd, recombination oramplification of signal occurs which results in a more appropriate information rendered to be coded and decoded in the next phase of infection. This has happened in this virus as follows: SARS-CoV1 TO SARS-CoV2.

The Quantum Information theory is superimposed in two interdependent states we may call it non-infective say 0 and infective state say 1. We may have ample number of states between non-infective and infective states. The virus is both infective and non-infective at the same time $t = 0$, however it may exist in either of these forms at $t > 0$. So temporal aspect of the virus cycle is important to note. A corollary can be drawn as at $t = 0.01$, at $t > 0$, 0…..1.

Let's have a look at this equation,

$$I = \text{iobits}$$

$$N = \text{Neobits}$$

$$C = \text{Cubits}$$

$$T = \text{Charge (+ve, −ve)}$$

$$T = C = N = I$$

$$T = C = (N_1 + N_2) = (I_1 + I_2)$$

$$T = C4(I_1 + I_2) + 2(N_1 + N_2)$$

$$T = C = (N_1 = I_1 + I_2 + I_3 + I_4) + (N_2 + I_5 + I_6 + I_7 + I_8)$$

$$T = C = N_1(I_{1\text{-}4}) + N_2(I_{5\text{-}8})$$

$$T = C$$

$$C = N_1 + N_2$$

$$N_1 = (I_1 + I_2)$$

$$N_2 = (I_3 + I_4)$$

$$C = N_1(I_1 + I_2) + N_2(I_3 + I_4)$$

$$T = C = N_1(I_1 + I_2) + N_2(I_3 + I_4)$$

$$T = C = N_1(I_1 + I_2) + N_2(I_3 + I_4)$$

$$T = C_1 + C_2 = N_1(I_1 + I_2) + N_2(I_2 + I_4)$$

So, this superimposed information can be decoded in advance before any virus becomes infectious and communicable. Here is the diagram that makes it clearer in **Figure 1**.

5. Conclusion

That quantum phenomena might be observable in the messy world of living systems is historically a pejorative idea. While quantum theories accurately describe the behavior of the individual particles making up all matter, scientists have long presumed that the mass action of billions of particles jostling around at ambient temperature drowns out any weird quantum effects and is better explained by the more familiar rules of classical mechanics formulated by Isaac Newton and

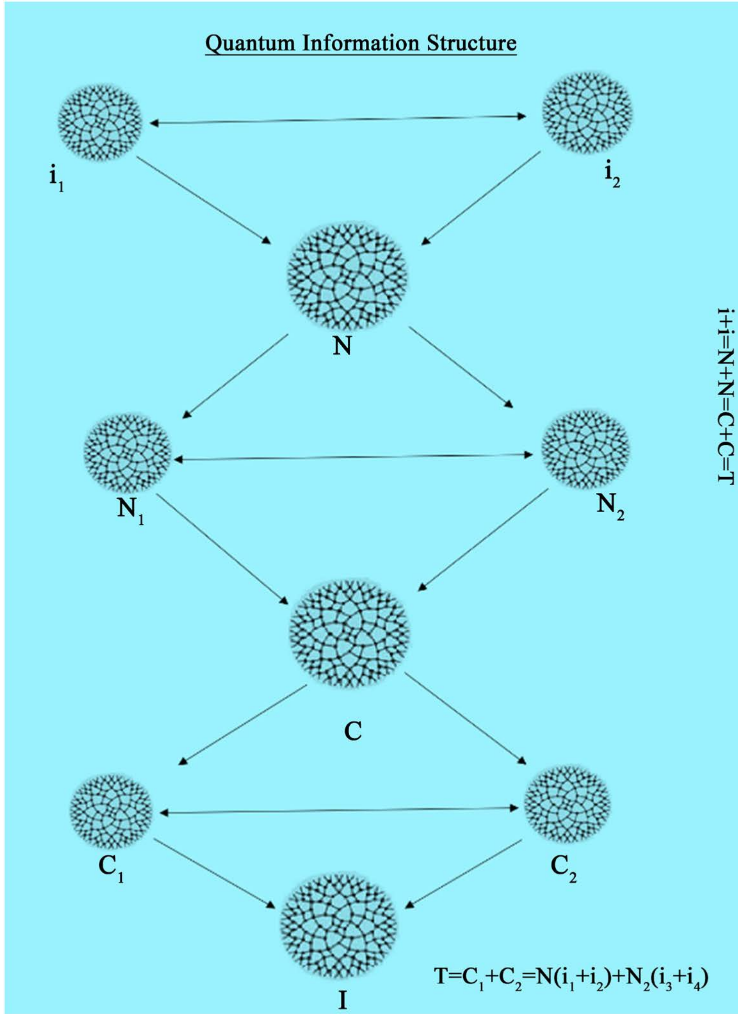

Figure 1. QIT Structure layout.

others [9].

1) Indeed, researchers studying quantum phenomena often isolate particles at temperatures approaching absolute zero—at which almost all particle motion grinds to a halt—just to quash the background noise [10].

2) "The warmer the environment is, the busier and noisy it is, the quicker these quantum effects disappear", says University of Surrey theoretical physicist Jim Al-Khalili, who coauthored a 2014 book called *Life on the Edge* that brought so-called quantum biology to a lay audience. "So it's almost ridiculous, counterintuitive, that they should persist inside cells. And yet, if they do—and there's a lot of evidence suggesting that in certain phenomena they do—then life must be doing something special [11]".

3) Al-Khalili and Vedral are part of an expanding group of scientists now arguing that effects of the quantum world may be central to explaining some of biology's greatest puzzles—from the efficiency of enzyme catalysis to avian navigation to human consciousness—and could even be subject to natural selection [12].

4) In the words of Chiara Marletto "The whole field is trying to prove a point", a University of Oxford physicist who collaborated with Coles and Vedral on the bacteria-entanglement paper. "That is to say, not only does quantum theory apply to these [biological systems], but it's possible to test whether these [systems] are harnessing QIT to perform their functions [13]".

5) Outbreaks of emerging and reemerging pathogens across the globe can be prevented with the help of QIT to minimize the disease burden locally and globally [14].

About the Author

Dr. Shahzad Aasim is a renowned Scientist working as Director at Haldia Institute of Fundamental Research, Kolkatta. He is also the Chairman of Kashmir Advanced Scientific Research Centre (KASRC). His research includes how Quantum theory reveals the Secrets of Nature.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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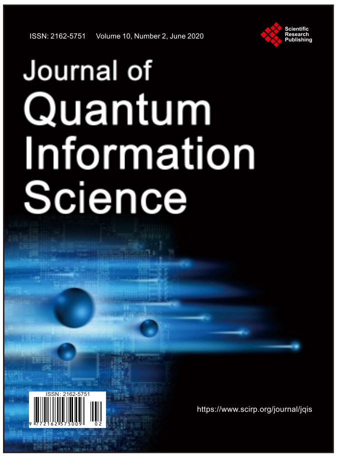

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