Practically secure quantum bit commitment based on quantum seals

Guang Ping He
School of Physics & Engineering and Advanced Research Center, Sun Yat-sen University, Guangzhou 510275, China
and Center of Theoretical and Computational Physics, The University of Hong Kong, Pokfulam Road, Hong Kong, China

Z. D. Wang
Department of Physics and Center of Theoretical and Computational Physics, The University of Hong Kong, Pokfulam Road, Hong Kong, China

The relationship between the quantum bit commitment (QBC) and quantum seal (QS) is studied. It is elaborated that QBC and QS are not equivalent, but QS protocols satisfying a stronger unconditional security requirement can lead to an unconditionally secure QBC. In this sense, QS is strictly stronger than QBC in security requirements. Based on an earlier proposal on sealing a single bit, a feasible QBC protocol is also put forward, which is secure in practice even if the cheater has a strong quantum computational power.

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I. INTRODUCTION

Bit commitment (BC) is a cryptographic task between two participants Alice and Bob. It normally includes two phases. In the commit phase, Alice in mind a bit (b = 0 or 1) which she wants to commit to Bob, and sends him a piece of evidence. Later, in the unveil phase, Alice announces the value of b, and Bob checks it with the evidence. A BC protocol is said to be binding if Alice cannot change the value of b after the commit phase, and is said to be concealing if Bob cannot know b before the unveil phase. A secure BC protocol needs to be both binding and concealing. Quantum bit commitment (QBC) is known to be an essential element for building more complicated “post-cold-war era” multi-party cryptographic protocols, e.g., quantum coin tossing and quantum oblivious transfer. Unfortunately, according to the Mayers-Lo-Chau (MLC) no-go theorem, unconditionally secure QBC does not seem to exist in principle. On the other hand, quantum seals (QS) are relatively new to quantum cryptography. Its goal can be summarized as follows. Alice, the owner of the secret data to be sealed, encodes the data with quantum states. Any reader Bob can obtain the data from these states without the help of Alice, while reading the data should be detectable by Alice. A QS protocol is considered to be secure if it possesses the following feature: Bob cannot escape Alice’s detection once he reads the data, namely, Bob is unable to read the data if he wants to escape Alice’s detection. QS can be classified by the types and the readability of the sealed data. If the data is a classical bit, it is called quantum bit seals (QBS). Else if the data is a classical string, it is called quantum string seals (QSS). If the data can always be obtained by the reader with certainty, it is called a perfect QS. Else if the data can only be obtained with a small but non-vanished error rate, it is an imperfect QS. The first perfect QBS protocol was proposed by Bechmann-Pasquinucci, but then it was proven that all perfect QBS ones are insecure against collective measurements. Shortly later, it was also found that imperfect QS has security limits. Nevertheless, the imperfect QSS can be secure. More intriguingly, it was proposed in Ref. that secure QS can be utilized to realize a kind of QBS, which is secure in practice.

Though QBC and QS may look like irrelevant at the first glance, here we elaborate that they are closely related. More rigorously, it will be shown below that a QBS protocol satisfying certain security conditions can lead to an unconditionally secure QBC. Based on the method of realizing QBS with QSS in Ref., a new QBC protocol is obtained. A most intriguing feature of this QBC protocol is that the present QBS protocol enables the secret data to be decoded with common senses of human being, thus it is very easy for an honest participant. On the contrary, a dishonest participant cannot fulfill the coherent attacks even if he has a very powerful quantum computer that can perform any kind of quantum operations and measurements. Instead, he needs also a knowledge base that has almost all knowledge of human culture, and his quantum computer needs to have a high level of artificial intelligence to handle these knowledge. This is impossible not only for current technology, but also is less likely in practice even in the future, because human intelligence seems to contain non-computable elements. In this sense, the present QBC protocol may be viewed as “practically secure”. Moreover, this QBC is quite feasible. Thus it is possible to build more complicated QBC-based multi-party cryptographic protocols and to enjoy the advantage of quantum cryptography in practice, even though the MLC no-go theorem is still

*Electronic address: hegp@mail.sysu.edu.cn
†Electronic address: zwang@hkuc.hku.hk
there.

II. THE RELATIONSHIP BETWEEN QUANTUM BIT COMMITMENT AND QUANTUM SEALS

For a QBS protocol with a known error rate $\varepsilon$, we can build a QBC protocol as follows (note that in this section, the names Alice and Bob are called contrarily to those in the description of QS in the Introduction, because the QBS protocol is executed in the reverse direction in the QBC protocols below).

The Basic Protocol

The commit phase:

(1) Bob randomly chooses $s$ bits $x_i$ ($i = 1, \ldots, s$), and seals each bit into a quantum register $\psi_i$ ($i = 1, \ldots, s$) with the QBS protocol. Then he sends these quantum registers to Alice.

(2) Alice randomly chooses $m$ of the quantum registers and decodes their corresponding sealed bits. She checks if the values of these $m$ sealed bits are random. She also asks Bob to reveal the values of the sealed bits for these $m$ quantum registers to check if they match the values she decoded within the error rate $\varepsilon$. If no suspicious result was found, Alice and Bob discard the data for these $m$ quantum registers and proceed.

(3) Alice randomly chooses one of the remaining $s - m$ quantum registers (suppose that it is $\psi_{i_0}$), decodes the sealed bit $x_{i_0}$, and leaves the rest $s - m - 1$ quantum registers unmeasured. Now she has in mind the value of the bit $b$ she wants to commit, and announces to Bob the value of $a = x_{i_0} \oplus b$.

The unveil phase:

(4) Alice announces to Bob the value of the commit bit $b$ and $i_0$, and sends Bob all the $s - m - 1$ unmeasured quantum registers.

(5) Bob uses the value $x_{i_0}$ he sealed in $\psi_{i_0}$ to check whether $a = x_{i_0} \oplus b$, and he checks whether the $s - m - 1$ quantum registers Alice returns him in this phase are indeed unmeasured, i.e., the corresponding sealed bits have not been decoded. He accepts Alice’s commitment as honest if no suspicious result was found.

This protocol is concealing because Bob cannot know $i_0$ before the unveil phase, since Alice’s announcing $a$ provides him 1 bit of information only, while locating $i_0$ requires $\log_2(s - m - 1)$ bits of information. Therefore Bob does not know $x_{i_0}$, so he cannot infer the value of the commit bit $b$ from Alice’s announced $a$, as long as each $x_i$ has the equal probabilities to be 0 or 1 (that is why Alice needs to check in step (2) whether the values of the sealed bits are random). It is also binding because if Alice wants to change the value of $b$ in the unveil phase, she has to find another quantum register $\psi_{i_1}$ whose sealed bit is $x_{i_1} = \bar{x}_{i_0}$, and sends $\psi_{i_0}$ to Bob as an unmeasured quantum register in step (5). But if the QBS protocol used in this QBC protocol is secure, Bob will detect that the bit sealed in $\psi_{i_0}$ has already been decoded, and catch Alice cheating.

However, Alice can apply the following weak cheating strategy. She measures no register in step (3), and announces a random value as $a$. Then in the unveil phase, she randomly chooses a register as $\psi_{i_0}$, and determines what value of $b$ can be announced in step (4) according to the decoding result of her current measurement on $\psi_{i_0}$ and the value of $a$ she previously announced. This may not be considered as a “real” cheating because Alice cannot announce $b$ at her will in the unveil phase. It is like tossing a coin and decide the value of $b$ by the head or tail. But on the other hand, it is also true that the protocol cannot limit Alice to honest behaviors because she is not forced to make up her mind on the value of $b$ during the commit phase. To fix this problem, we can further improve the protocol.

The Advanced Protocol

The commit phase:

(i) Alice and Bob agree on the security parameters $s$, $m$ and $n$ ($n << s - m$), and a Boolean matrix $G$ as the generating matrix of a binary linear $(n, k, d)$-code $C$ [10].

(ii) The same as steps (1) and (2) of the basic protocol.

(iii) Alice randomly chooses $n$ of the remaining $s - m$ quantum registers. Suppose that they are $\psi_j$ ($j = i_1, i_2, \ldots, i_n$, $i_1 < i_2 < \cdots < i_n$). She decodes each of the bit $x_j$ sealed in these $n$ registers, and leaves the rest $s - m - n$ quantum registers unmeasured. Thus she obtains a classical $n$-bit string $x = (x_{i_1}, x_{i_2}, \ldots, x_{i_n})$.

(iv) Alice chooses a non-zero random $n$-bit string $r = (r_1, r_2, \ldots, r_n) \in \{0, 1\}^n$ and announces it to Bob;

(v) Now Alice has in mind the value of the bit $b$ that she wants to commit. She chooses an $n$-bit codeword $c = (c_1, c_2, \ldots, c_n)$ from $C$ such that $c \oplus r = b$ (Here $c \oplus r \equiv \bigoplus_{i=1}^{n} c_i \land r_i$);

(vi) Alice announces to Bob $c' = c \oplus x$.

The unveil phase:

(vii) Alice announces to Bob the value of the commit bit $b$ and $i_1, i_2, \ldots, i_n$, and sends Bob all the $s - m - n$ unmeasured quantum registers.

(viii) Bob uses the values $x_j$ he sealed in $\psi_j$ ($j = i_1, i_2, \ldots, i_n$) to obtain $c$ from $c' = c \oplus x$, and checks whether $c$ is indeed a codeword from $C$ and $c \oplus r = b$. He also checks whether the $s - m - n$ quantum registers Alice sends him in this phase are indeed unmeasured, and accepts Alice’s commitment as honest if no suspicious result was found.

The intuition behind this protocol is that if Alice wants to keep the value of $b$ undetermined in the commit phase by measuring less than $n$ registers in step (iii), she has
to announce $c'$ randomly in step (vi) since she does not know $x$. Then in step (vii) of the unveil phase, she has to find the correct indices $i_1, i_2, ..., i_n$ to announce, so that the data $x = (x_{i_1}, x_{i_2}, ..., x_{i_n})$ sealed in $\psi_j$ $(j = i_1, i_2, ..., i_n)$ ensures that $c' \oplus x$ is a codeword from $C$. Generally, if she randomly chooses $n$ indices to announce while leaving the rest $s - m - n$ quantum registers completely unmeasured, the probability is trivial for the value of $x$ thus obtained to be exactly what needed. The question is whether the following strategy can be successful: In the unveil phase, Alice randomly chooses $n$ quantum registers and measures them with collective measurements instead of individual measurements, so that they can be less disturbed if their sealed data is not the desired $x$. Then Alice can repeat the procedure with other sets of $n$ registers, until she finally finds the set in which the desired $x$ is sealed. In this case, whether the above QBC protocol is secure or not will be determined by how much disturbance is caused by Alice’s collective measurements. That is, it is determined by the security level of the QBS protocol used in step (ii). To find out how secure this QBS needs to be, let us first review the classification of definitions of security of cryptographic protocols. Currently, the following two definitions of security are widely adopted [4].

**Perfect security:**
When the other participant(s) is (are) honest, the amount of extra information (other than what is allowed by the protocol) obtained by the dishonest participant(s) is exactly zero.

**Unconditional security:**
When the other participant(s) is (are) honest, the amount of extra information obtained by the dishonest participant(s) can be made arbitrarily small by increasing the security parameter(s) of the protocol.

Obviously when perfectly secure QBS protocols are used in Advanced Protocol, it will result in an unconditionally secure QBC. What we are interested is whether unconditionally secure QBS protocols are useful too. Note that the above definition of unconditional security is equivalent to: when the other participant(s) is (are) honest, the probability for a dishonest participant to obtain non-trivial amount of extra information while escaping the detection can be made arbitrarily small by increasing the security parameter(s) of the protocol. However, it was left blank in this definition whether the probability for a dishonest participant to escape the detection can be made arbitrarily small if he obtains trivial amount of extra information only. To be rigorous, here we propose an independent definition for a kind of unconditionally secure protocols which satisfies stricter security requirement.

**Strong unconditional security:**
When the amount of extra information obtained by a dishonest participant is $f(n)$ (here $f(n)$ is a function whose value decreases as the security parameter(s) $n$ of the protocol increases), the probability for him to escape the detection by the honest participant(s) is $o(\alpha^f(n))$. Here the constant $\alpha$ satisfies $0 < \alpha < 1$.

Now let us see what difference will be made when different kinds of unconditionally secure QBS protocols are used in the above Advanced QBC Protocol. Suppose that Alice applies the cheating strategy mentioned above. She measures no quantum registers in the commit phase. In the unveil phase, she randomly chooses $n$ registers and measures them with collective measurements. If it turns out that the data sealed in these registers is exactly the desired $x$ that could lead to the value of $b$ she wants to unveil, then her cheating is successful. Else she tries again with another set of $n$ registers. Note that in the latter case, she merely knows that the data sealed in the first $n$ registers she measured is not $x$, while she does not know what exactly the sealed data is. Thus the amount of information she obtained is merely $f(n)$. If general unconditionally secure QBS protocols are adopted which do not satisfy the strong unconditional security condition, Alice can escape the detection with a probability not less than $O(\alpha^f(n))$. Suppose that it averagely takes $t$ times for Alice to perform collective measurements on different sets of $n$ registers until she finds the desired $n$ registers which give the outcome $x$ she is looking for. Since the goal of Alice is to commit 1 bit of information, we have $tf(n) \sim O(1)$, i.e., $tf(n)$ has a finite non-trivial value. Then the probability for Alice to escape the detection will be not less than $[O(\alpha^f(n))]^t \sim O(\alpha^{tf(n)})$, which also remains finite instead of being trivial as $n$ increases. Thus we come to the conclusion that unconditionally secure QBS which does not satisfy the strong unconditional security condition does not necessarily lead to unconditionally secure QBC through the above Advanced Protocol.

On the other hand, if strong unconditionally secure QBS protocols are adopted in Advanced Protocol, whenever Alice measures $n$ registers and obtains $f(n)$ bits of information, she can escape the detection with probability $o(\alpha^{f(n)})$ only. That is, when she finally finds the $n$ registers she is looking for and thus obtains finite non-trivial amount of information, the probability for her to escape the detection will be $\sim o(\alpha^{f(n)})$, which does not remain finite. Instead, it drops arbitrarily close to zero as $n$ increases. Consequently, the resultant QBC protocol is unconditionally secure. Therefore we reach one of the main result of this paper: strong unconditionally secure QBS can lead to unconditionally secure QBC.

It is natural to ask a further question whether strong unconditionally secure QBS and unconditionally secure QBC are equivalent. So far, to our best knowledge, no unconditionally secure QBS protocol based on unconditionally secure QBC (no matter it exists or not) was ever proposed. It is also worth noting that the definitions of QBS and QBC indicate a significant different feature between them. In the final stage of QBC, Alice needs to
unveil to Bob what she committed, i.e., classical communication is needed. On the contrary, in QBS Alice can check whether the sealed data was decoded or not at any time, with or without the classical communication from Bob. Therefore it seems reasonable that an unconditionally secure QBS protocol based on unconditionally secure QBC does not exist at all. For these reasons, we tend to believe that strong unconditionally secure QBS and unconditionally secure QBC are not equivalent. Strong unconditionally secure QBS is strictly stronger than unconditionally secure QBC in security requirements.

### III. PRACTICALLY SECURE QUANTUM BIT COMMITMENT PROTOCOL

In Ref. [8], a model of QBS was proposed and it was proven that any QBS satisfying this model cannot be unconditionally secure. To date, the model seems to cover all QBS protocols within our current imagination. Consequently, before we can come up with a protocol which satisfies the definition of QBS exactly while is not covered by that model, unconditionally secure QBS does not seems to exist in principle. Therefore no QBS can lead to unconditionally secure QBC via the above Advanced Protocol. Nevertheless, it was shown in Ref. [8] that unconditionally secure QSS exits, and it can lead to QBS which is secure in practice. Therefore we can use this QBS to realize a kind of QBC which is also secure in practice.

Let us briefly review the QSS and QBS protocols proposed in Ref. [8]. Let \( \Theta (0 < \Theta \ll \pi/4) \) and \( \alpha (0 < \alpha < 1/2) \) be two fixed constants. The proposed QBS protocol is as follows.

**Sealing:** To seal a classical \( N \)-bit string \( b = b_1b_2...b_N \) \( (b_i \in \{0,1\}) \), Alice randomly chooses \( \theta_i (\Theta/N^\alpha \leq \theta_i \leq \Theta/N^\alpha) \) and encodes each bit \( b_i \) with a qubit in the state \(|\psi_i\rangle = \cos \theta_i |b_i\rangle + \sin \theta_i |\bar{b}_i\rangle \). She makes these \( n \) qubits publicly accessible to the reader, while keeping all \( \theta_i (i = 1,...,N) \) secret.

**Reading:** When Bob wants to read the string \( b \), he simply measures each qubit in the computational basis \( \{|0\rangle,|1\rangle\} \), and denotes the outcome as \(|b'_i\rangle\). He takes the string \( b' = b'_1b'_2...b'_N \) as \( b \).

**Checking:** At any time, Alice can check whether the sealed string \( b \) has been read by trying to project the \( i \)-th qubit \( (i = 1,...,N) \) into \( \cos \theta_i |b_i\rangle + \sin \theta_i |\bar{b}_i\rangle \). If all the \( N \) qubits can be projected successfully, she concludes that the string \( b \) is still unread. Otherwise if any of the qubits fails, she knows that \( b \) is read.

This protocol can achieve the following goal: each bit sealed by Alice can be read correctly by Bob, except with a probability not greater than \( \varepsilon = \sin^2(\Theta/N^\alpha) \). Thus by increasing \( N \), the maximal reading error rate \( \varepsilon \) can be made arbitrarily small. Meanwhile, the total probability for Bob to obtain \( K \) bits of information while escaping the detection is bounded by

\[
P \leq 2^{-K} \prod_{i=1}^{N} 2 \cos^2 \theta_i,
\]

which drops exponentially as \( K \to N \), and vanishes when \( N \to \infty \) as long as \( 0 < \alpha < 1/2 \). Thus the protocol is unconditionally secure in principle.

This QSS protocol can be utilized to seal a single bit. The method is to turn the sealed bit into a string by adding redundant information. There are many ways to accomplish this. In the simplest case, we can map some global properties of the string, e.g., the parity or the weight, into the bit we want to seal. But since such kinds of mapping is easy to be formulated mathematically, a cheater with a powerful quantum computer can construct a proper collective measurement corresponding to the mapping, and reads the sealed bit with the strategy proposed in Ref. [8] so that he can escape the detection with a non-trivial probability. Hence the protocol is easy to be broken. But in practice, we can make it more difficult to know the rule of the mapping dishonestly than to do so honestly. One of such methods is to translate the sentences describing the rules of the mapping into a classical binary bit string, and seal it as a part of the sealed string so that the cheater does not know the mapping before decoding the string.

For example, Alice can first encode the following sentence into a classical binary bit string

\[
\text{"Measure the last two qubits in the basis}\{\cos 15^\circ |0\rangle + \sin 15^\circ |1\rangle, -\sin 15^\circ |0\rangle + \cos 15^\circ |1\rangle\} \quad \text{and you will know the value of the sealed bit from their parity. Other qubits following this sentence are all dummy qubits. You can simply leave them alone."}
\]

Then she seals it with our QSS protocol, and provides Bob the qubits encoding this sentence, followed by a large number of qubits where only the last two are actually useful.

We must point out that this bit sealing method is still insecure in principle. This is because any given classical \( N \)-bit string can be decoded into one specific sentence only, and the meaning of the sentence will lead to a value of the sealed bit unambiguously. As long as a dishonest Bob knows the length \( N \) of the sealed string, he can study all the \( 2^N \) possible classical \( N \)-bit strings, decode them into sentences, and divide these sentences into two subsets corresponding to the two possible value of the sealed bit (of course there will also be tons of meaningless sentences and even random sequences of bits that cannot be decoded as sentences. Bob can simply leave them alone). Then as described in Ref. [8], he needs not to know the content of the sealed sentence exactly. He simply constructs a proper collective measurement to determine which subset the sentence belongs to. Thus
he will know the sealed bit from the $N$ qubits without disturbing them seriously.

Nevertheless, if $N$ is sufficiently large, the number of possible sentences will be enormous. There could be sentences as simple as

\[ \text{“It is 0. Ignore the rest qubits.”} \]

But there are also sentences like

\[ \text{“Decode the bits following this sentence as a bitmap image and count the parity of the number of females.”} \]

and followed by the bits encoding an image of animals, or famous cartoon icons, or a picture as shown in Fig. 1. For an honest participant who does not mind disturbing the quantum state sealing the string, he can simply decode the whole string and learn the value of the sealed bit easily. But for a dishonest participant who wants to keep the quantum state less disturbed so that he can escape the detection, he does not know beforehand what kind of the sentences he will encounter. To decode the sealed bit with collective measurements, he has to build a data base which contains all sentences, pictures, and even wave files for voice messages, etc., which can be encoded as $N$-bit strings. More importantly, learning the sealed bit from pictures such as Fig. 1 is easy for human beings with common senses, while if it is expected to be done by machine, it has to have advanced power on image identifying, pattern matching, and the capability to understand the meaning of pictures, which may require a large coverage of the knowledge of science and culture in human history. It is actually impossible in practice for a cheater to build such a data base for sufficiently large values of $N$, even he has the most powerful quantum computer. Thus his collective measurements cannot be constructed. In this sense, such QBS can be viewed as secure in practice.

With the above results of Ref. [9], building a QBC protocol is straightforward. We can simply apply this “practically secure” QBS protocol in Advanced Protocol to obtain a QBC protocol. Note that the “practically secure” QBS does not satisfy the strong unconditional security condition. In fact, it is not unconditionally secure in principle at all. Consequently, the resultant QBC protocol is not unconditionally secure in principle. But since the above QBS cannot be broken in practice, the resultant QBC, whose security completely determined by the QBS protocol being based on, is also secure in practice. Especially, when $N$ is sufficiently large, there will inevitably some sequences of bits which can be decoded incidentally as sentence like

\[ \text{“Go to the main library. Find the book on the top – left of the last shelf. Turn to the last page, and count how many times the letter K occurs in the 3rd line....”} \]

Though such a sentence may lead to a deterministic value of the sealed bits, it is less likely that the bit is really sealed this way according to common sense. Therefore a cheater can simply keep such sentences out of consideration in a QBS protocol. Nevertheless, in our QBC protocol we can allow Bob (again, please note that the names Alice and Bob called in Advanced Protocol are contrary to those in QBS) to seal such ridiculous sentences (and even meaningless sentences which is literally correct but may contain no clue for the sealed bit) with a certain probability which is also agreed by Alice. Whenever Alice decodes such a sentence in step (iii), she can tell Bob to discard the corresponding data and chooses another quantum register to measure. This will make the protocol even more secure because if Alice wants to cheat, her quantum computer will also have to deal with all ridiculous and meaningless sentences, and judge which sentences make sense. To accomplish this, it seems that the quantum computer needs not only unlimited computational power to perform any kind of quantum operation and measurement, but also some extent of artificial intelligence. So far there is even debate on whether human intelligence is computable or not [15]. Therefore the security of our protocol is further guaranteed by those incomputable elements. As a result, though the MLC no-go theorem is considered to have put a serious drawback on the development of the theoretical aspect of quantum cryptography, in practice we can simply bypass this theorem and go ahead with this “practically secure” QBC protocol. After all, the main purpose of developing cryptography is to satisfy the application needs of human society, which involve not only physical and mathematical principles, but also human behaviors. Cheating itself is exactly a creation of human intervention. Therefore it is natural to introduce more human-related issues into cryptography to prevent cheating. Our finding makes it possible to building any complicated QBC-based “post-cold-war era” multi-party cryptographic protocols, like
quantum coin tossing and quantum oblivious transfer, and achieve better security in practice which cannot be reached by their classical counterparts.

IV. FEASIBILITY

The present QBC protocol can be implemented as long as the based-on QS protocol can be realized. As pointed out in Ref. [9], the QS protocol requires merely Alice to have the ability to prepare each single qubit in a pure state, and Bob to perform individual measurements. No entanglement/collective-measurement is required. Therefore the protocol may be demonstrated and verified by the techniques available currently. Of course for practical uses, storing quantum states for a long period of time is still a technical challenge today. But this is a tough issue that all QS protocols have to suffer. The present protocol may be one of the simplest protocols of its kind. More significantly, if such technique of storing quantum states is not available, the attack strategy proposed by the MLC no-go theorem that makes previous QBC (e.g., Ref. [1]) insecure cannot be implemented either; but on the other hand, whenever this tough technical problem is resolved in the future, the previous QBC would be broken quite easily, while our QBC protocol may still remain to be secure in practice.

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