

## MIT Open Access Articles

*Generation of universal linear optics by any beam splitter*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

**Citation:** Bouland, Adam, and Scott Aaronson. "Generation of Universal Linear Optics by Any Beam Splitter." Phys. Rev. A 89, no. 6 (June 2014). © 2014 American Physical Society

**As Published:** <http://dx.doi.org/10.1103/PhysRevA.89.062316>

**Publisher:** American Physical Society

**Persistent URL:** <http://hdl.handle.net/1721.1/88647>

**Version:** Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

**Terms of Use:** Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.





# Generation of universal linear optics by any beam splitter

Adam Bouland<sup>\*</sup> and Scott Aaronson<sup>†</sup>

*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 25 October 2013; revised manuscript received 10 May 2014; published 16 June 2014)

In 1994, Reck *et al.* showed how to realize any unitary transformation on a single photon using a product of beam splitters and phase shifters. Here we show that any *single* beam splitter that nontrivially mixes two modes also densely generates the set of unitary transformations (or orthogonal transformations, in the real case) on the single-photon subspace with  $m \geq 3$  modes. (We prove the same result for any two-mode real optical gate, and for any two-mode optical gate combined with a generic phase shifter.) Experimentally, this means that one does not need tunable beam splitters or phase shifters for universality: any nontrivial beam splitter is universal for linear optics. Theoretically, it means that one cannot produce “intermediate” models of linear optical computation (analogous to the Clifford group for qubits) by restricting the allowed beam splitters and phase shifters: there is a dichotomy; one either gets a trivial set or else a universal set. No similar classification theorem for gates acting on qubits is currently known. We leave open the problem of classifying optical gates that act on three or more modes.

DOI: [10.1103/PhysRevA.89.062316](https://doi.org/10.1103/PhysRevA.89.062316)

PACS number(s): 03.67.Lx, 42.50.-p, 42.79.Fm

## I. INTRODUCTION

Universal quantum computers have proved difficult to build. As one response, researchers have proposed limited models of quantum computation, which might be easier to realize. Three examples are the one clean qubit model of Knill and Laflamme [1], the commuting Hamiltonians model of Bremner, Jozsa, and Shepherd [2], and the boson sampling model of Aaronson and Arkhipov [3]. None of these models are known or believed to be capable of universal quantum computation (or, depending on modeling details, even universal *classical* computation). But all of them can perform certain estimation or sampling tasks for which no polynomial-time classical algorithm is known.

One obvious way to define a limited model of quantum computation is to restrict the set of allowed gates. However, almost every gate set is universal [4], and so are most “natural” gate sets. For example, controlled-NOT together with any real one-qubit gate that does not square to the identity is universal [5]. As a result, very few nontrivial examples of nonuniversal gate sets are known. All known nonuniversal gate sets on  $O(1)$  qubits, such as the Clifford group [6], are efficiently classically simulable, if the input and measurement outcomes both belong to an appropriately chosen qubit basis.<sup>1</sup> As a result, it is tempting to conjecture that there does not *exist* such an intermediate gate set: or more precisely, that any gate set on  $O(1)$  qubits is either efficiently classically simulable

(with appropriate input and output states), or else universal for quantum computing. Strikingly, this dichotomy conjecture remains open even for the special case of 1- and 2-qubit gates. We regard proving or disproving the conjecture as an important open problem for quantum computing theory. In this paper, we prove a related conjecture in the quantum linear optics model. In quantum optics, the Hilbert space is not built up as a tensor product of qubits; instead it is built up as a direct *sum* of optical modes. An optical *gate* is then just a unitary transformation that acts nontrivially on  $O(1)$  of the modes, and as the identity on the rest. Whenever we have a  $k$ -mode gate, we assume that we can apply it to any subset of  $k$  modes (in any order), as often as desired. The most common optical gates considered are *beam splitters*, which act on two modes and correspond to a  $2 \times 2$  unitary matrix with determinant  $-1$ ,<sup>2</sup> and *phase shifters*, which act on one mode and simply apply a phase  $e^{i\theta}$ . Note that any unitary transformation acting on the one-photon Hilbert space automatically gets “lifted,” by homomorphism, to a unitary transformation acting on the Hilbert space of  $n$  photons. Furthermore, every element of the  *$n$ -photon linear-optical group*—that is, every  $n$ -photon unitary transformation achievable using linear optics—arises in this way (see [3], Sec. III, for details). Of course, if  $n \geq 2$ , then there are also  $n$ -photon unitaries that cannot be achieved linear-optically: that is, the  $n$ -photon linear-optical group is a proper subgroup of the full unitary group on the  $n$ -photon Hilbert space. We call a set of optical gates  *$S$  universal* on  $m$  modes if it generates a dense subset of either  $SU(m)$  (in the complex case) or  $SO(m)$  (in the real case). To clarify, if  $S$  is universal, this does not mean that linear optics with  $S$  is universal for quantum computing. It only means that  $S$  densely generates the one-photon linear-optical group—or equivalently, the  $n$ -photon linear-optical group for any value

<sup>\*</sup>adam@csail.mit.edu

<sup>†</sup>aaronson@csail.mit.edu

<sup>1</sup>But not necessarily otherwise. For instance, suppose that a nonuniversal gate set  $G$  is efficiently simulable if inputs and outputs are in the computational basis. Now conjugate  $G$  by a change of qubit basis to obtain a gate set  $G'$ . Clearly  $G'$  is efficiently classically simulable in the new qubit basis. However, it is unclear how to simulate the gates  $G'$  if inputs and outputs are in the computational basis. Along these lines, there is evidence that Clifford gates [7], permutation gates [8], and even diagonal gates [2] can be hard to simulate in arbitrary bases.

<sup>2</sup>Some references use a different convention and assume that beam splitters have determinant  $+1$  [9]. Note that these two conventions are equivalent if one assumes that one can permute modes, i.e., apply the matrix  $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$  which has determinant  $-1$ .

of  $n$ . The latter kind of universality is certainly *relevant* for quantum computation: first, it already suffices for the boson sampling proposal of Aaronson and Arkhipov [3], and second, if the single resource of adaptive measurements is added, then universal linear optics becomes enough for universal quantum computation, by the famous result of Knill, Laflamme, and Milburn (KLM) [10]. On the other hand, if we wanted to map a  $k$ -qubit Hilbert space *directly* onto an  $m$ -mode linear-optical Hilbert space, then as observed by Cerf, Adami, and Kwiat [11], we would need  $m \geq 2^k$  just for dimension-counting reasons. Previously, Reck *et al.* [12] showed that the set of *all* phase shifters and all beam splitters is universal for linear optics, on any number of modes. Therefore it is natural to ask, is there *any*  $S$  set of beam splitters and phase shifters that generates a nontrivial set of linear-optical transformations, yet that still falls short of generating *all* of them? Here by “nontrivial,” we simply mean that  $S$  does *something* more than permuting the modes around or adding phases to them. If such a set  $S$  existed, we could then ask the *further* question of whether the  $n$ -photon subgroup generated by  $S$  was

- (a) efficiently simulable using a classical computer, despite being nontrivial (much like the Clifford group for qubits),
- (b) already sufficient for applications such as boson sampling and KLM, despite not being the full  $n$ -photon linear-optical group, or
- (c) of “intermediate” status, neither sufficient for boson sampling and KLM nor efficiently simulable classically.

The implications for our dichotomy conjecture would of course depend on the answer to that further question.

In this paper, however, we show that the further question never even arises, since *no such set  $S$  exists*. Indeed, any beam splitter that acts nontrivially on two modes is universal on three or more modes. What makes this result surprising is that it holds *even if the beam splitter angles are all rational multiples of  $\pi$* . *A priori*, one might guess that by restricting the beam splitter angles to (say)  $\pi/4$ , one could produce a linear-optical analog of the Clifford group, but our result shows that one cannot.

Our proof uses standard representation theory and the classification of closed subgroups of  $SU(3)$  [13–15]. From an experimental perspective, our result shows that any complex nontrivial beam splitter suffices to create any desired optical network. From a computational complexity perspective, it implies a dichotomy theorem for optical gate sets: any set of beam splitters or phase shifters generates a set of operations that is either *trivially* classically simulable (even on  $n$ -photon input states), or else universal for quantum linear optics. In particular, any nontrivial beam splitter can be used to perform boson sampling; there is no way to define an “intermediate” model of boson sampling<sup>3</sup> by restricting the allowed beam splitters and phase shifters.

Note that our result holds only for beam splitters, i.e., optical gates that act on two modes and have determinant  $-1$ . We leave as an open problem whether our result can be extended to arbitrary two-mode gates, or to gates that act on three or more modes.

Our work explores limiting the power of quantum linear optics by limiting the gate set. Previous work has considered varying the available input states and measurements. For example, as mentioned earlier, Knill, Laflamme, and Milburn [10] showed that linear optics with adaptive measurements is universal for quantum computation. Restricting to nonadaptive measurements seems to reduce the computational power of linear optics, but Aaronson and Arkhipov [3] gave evidence that the resulting model is still impossible to simulate efficiently using a classical computer. If Gaussian states are used as inputs and measurements are taken in the Gaussian basis only, then the model is efficiently simulable classically [16], but with Gaussian-state inputs and *photon-number* measurements, there is recent evidence for computational hardness [17].

We hope that this work will serve as a first step toward proving the dichotomy conjecture for *qubit*-based quantum circuits (i.e., the conjecture that every set of gates is either universal for quantum computation or else efficiently classically simulable). The tensor product structure of qubits gives rise to a much more complicated problem than the direct sum structure of linear optics. For that reason, one might expect the linear-optical “model case” to be easier to tackle first, and the present work confirms that expectation.

## II. BACKGROUND AND OUR RESULTS

In a linear optical system with  $m$  modes, the state of a photon is described by a vector  $|\psi\rangle$  in an  $m$ -dimensional Hilbert space. The basis states of the system are represented by strings  $|s_1, s_2, \dots, s_m\rangle$  where  $s_i \in \{0, 1\}$  denotes the number of photons in the  $i$ th mode, and  $\sum_{j=1}^m s_j$  is the total number of photons (in this case, one). For example a one-photon, three-mode system has basis states  $|100\rangle, |010\rangle$ , and  $|001\rangle$ .

A  $k$ -local gate  $g$  is a  $k \times k$  unitary matrix which acts on  $k$  modes at a time while acting in direct sum with the identity on the remaining  $m - k$  modes. A *beam splitter*  $b$  is a two-local gate with determinant  $-1$ . Therefore any beam splitter has the form  $b = \begin{pmatrix} \alpha & \beta^* \\ \beta & -\alpha^* \end{pmatrix}$ , where  $|\alpha|^2 + |\beta|^2 = 1$ . Let  $b_{ij}$  denote the matrix action of applying the beam splitter to modes  $i$  and  $j$  of a one-photon system. For example, if  $m = 3$ , we have that

$$b_{12} = \begin{pmatrix} \alpha & \beta^* & 0 \\ \beta & -\alpha^* & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad b_{31} = \begin{pmatrix} -\alpha^* & 0 & \beta \\ 0 & 1 & 0 \\ \beta^* & 0 & \alpha \end{pmatrix}$$

when written in the computational basis. A beam splitter is called *nontrivial* if  $|\alpha| \neq 0$  and  $|\beta| \neq 0$ , i.e., if the beam splitter mixes modes.

We say that a set  $S$  of optical gates *densely generates* a continuous group  $G$  of unitary transformations, if the group  $H$  generated by  $S$  is a dense subgroup of  $G$  (that is, if  $H \leq G$  and  $H$  contains arbitrarily close approximations to every element of  $G$ ). Then we call  $S$  *universal on  $m$  modes* if it densely generates  $SU(m)$  or  $SO(m)$  when acting on  $m$  modes. [Due to the irrelevance of global phases, this is physically equivalent to generating  $U(m)$  or  $O(m)$  respectively.] In this definition we are assuming that whenever we have a  $k$ -mode gate in  $S$ , we can apply it to any subset of  $k$  modes (in any order), as often as desired. Note that we consider real  $SO(m)$  evolutions

<sup>3</sup>Here by “intermediate,” we mean computationally intermediate between classical computation and universal boson sampling.

to be universal as well; this is because the distinction between real and complex optical networks is mostly irrelevant<sup>4</sup> to computational applications of linear optics, such as the KLM protocol [10] and boson sampling [3].

A basic result in quantum optics, proved by Reck *et al.* [12], says that the collection of all beam splitters and phase shifters is universal. Specifically, given any target unitary  $U$  on  $m$  modes, there exists a sequence of  $O(m^2)$  beam splitters and phase shifters whose product is exactly  $U$ . Reck *et al.*'s proof also shows an analogous result for real beam splitters—namely, that any orthogonal matrix  $O$  can be written as the product of  $O(m^2)$  real beam splitters. Furthermore, it can easily be shown that there exist two beam splitters  $b, b'$  whose products densely generate  $O(2)$ . Therefore  $b$  and  $b'$  can be used to simulate any real beam splitter, and hence by Reck *et al.* [12], the set  $\{b, b'\}$  is universal for linear optics.

In this paper, we consider the universality of a *single* beam splitter  $b$ . If  $b$  is trivial, then on  $m$  modes the matrices  $b_{ij}$  generate a subgroup of  $P_m$ , the set of  $m \times m$  unitary matrices with all entries having norm zero or one. This is obviously nonuniversal, and the state evolutions on any number of photons are trivial to simulate classically. Our main result is that any nontrivial beam splitter densely generates either all orthogonal transformations on three modes (in the real case), or all unitary transformations on three modes (in the complex case). From this, it follows easily from Reck *et al.* [12] that such a beam splitter is also universal on  $m$  modes for any  $m \geq 3$ .

**Theorem 1.** Let  $b$  be any nontrivial beam splitter. Then the set  $S = \{b_{12}, b_{13}, b_{23}\}$ , obtained by applying  $b$  to all possible pairs among three photon modes,<sup>5</sup> densely generates either  $SO(3)$  (if all entries of  $b$  are real) or  $SU(3)$  (if any entry of  $b$  is nonreal).

**Corollary 1.** Any nontrivial beam splitter is universal on  $m \geq 3$  modes.

**Proof.** By Theorem 1, the set  $S = \{b_{12}, b_{13}, b_{23}\}$  densely generates all orthogonal matrices with determinant 1. But since  $b$  has determinant  $-1$ , we know that  $S$  must generate all orthogonal matrices with determinant  $-1$  as well.<sup>6</sup> Therefore,  $S$  densely generates the action of any real beam splitter  $b'$  acting on two out of three modes. So by Reck *et al.* [12],  $S$  also densely generates all orthogonal matrices on  $m$  modes for  $m \geq 3$ . ■

Note that, although our proof of universality on three modes is nonconstructive, by the Solovay-Kitaev theorem [19], there is an efficient algorithm that, given any target unitary  $U$ , finds a

sequence of  $b$ 's approximating  $U$  up to error  $\varepsilon$  in  $O(\log^{3.97}(\frac{1}{\varepsilon}))$  time. Thus, our universality result also implies an efficient algorithm to construct any target unitary using beam splitters in the same manner as Reck *et al.* [12]. We now proceed to a proof of Theorem 1.

### III. PROOF OF MAIN THEOREM

We first consider applying a fixed beam splitter

$$b = \begin{pmatrix} \alpha & \beta^* \\ \beta & -\alpha^* \end{pmatrix},$$

where  $\alpha$  and  $\beta$  are complex and  $|\alpha|^2 + |\beta|^2 = 1$ , to two modes of a three-mode optical system. We take pairwise products of these beam splitter actions to generate three special unitary matrices. These three unitaries densely generate some group of matrices  $G \leq SU(3)$ . We then use the representation theory of subgroups of  $SU(3)$  described in the work of Fairbairn, Fulton, and Klink [13], Hanany and He [14], and Grimus and Ludl [15] to show that the beam splitter must generate either all  $SO(3)$  matrices (if the beam splitter is real) or all  $SU(3)$  matrices (if the beam splitter has a complex entry).

Consider applying our beam splitter to a three-mode system. Let  $R_1, R_2, R_3$  be defined as the pairwise products of the beam splitter actions below:

$$\begin{aligned} R_1 &= b_{12}b_{13} = \begin{pmatrix} \alpha^2 & \beta^* & \alpha\beta^* \\ \alpha\beta & -\alpha^* & |\beta|^2 \\ \beta & 0 & -\alpha^* \end{pmatrix}, \\ R_2 &= b_{23}b_{13} = \begin{pmatrix} \alpha & 0 & \beta^* \\ |\beta|^2 & \alpha & -\alpha^*\beta^* \\ -\alpha^*\beta & \beta & \alpha^2 \end{pmatrix}, \\ R_3 &= b_{12}b_{23} = \begin{pmatrix} \alpha & \alpha\beta^* & \beta^{*2} \\ \beta & -|\alpha|^2 & -\alpha^*\beta^* \\ 0 & \beta & -\alpha^* \end{pmatrix}. \end{aligned}$$

Since  $R_1, R_2, R_3$  are even products of matrices of determinant  $-1$ , they are all elements of  $SU(3)$ . Let  $G \leq SU(3)$  be the subgroup densely generated by products of the elements  $\{R_1, R_2, R_3\}$  and their inverses.<sup>7</sup> Let  $G_M$  be the set of matrices representing  $G$  under this construction. First we will show that these matrices  $G_M$  form an irreducible representation of  $G$ .

**Claim 1.** The set  $\{R_1, R_2, R_3\}$  generates an irreducible three-dimensional representation of  $G$ .

**Proof.** Suppose that some matrix

$$U = \begin{pmatrix} A & D & G \\ B & E & H \\ C & F & I \end{pmatrix}$$

commutes with  $R_1, R_2$ , and  $R_3$ . Then we claim that  $U$  is a constant multiple of the identity; i.e.,  $A = E = I$  and  $D = G = H = B = C = F = 0$ .

<sup>7</sup>Since  $b_{ij}^{-1} = b_{ij}$ , the beam splitter is capable of generating the inverses of the  $R_i$  as well.

<sup>4</sup>The one case we know about where the real vs complex distinction might matter is when using error-correcting codes. There, applying all possible orthogonal transformations to the physical modes or qubits might not suffice to apply all orthogonal transformations to the encoded modes or qubits. This could conceivably be an issue, for example, in the scheme of Gottesman, Kitaev, and Preskill [18] for universal quantum computing with linear optics.

<sup>5</sup>Technically, we could also consider the unitaries  $b_{21}, b_{31}, b_{32}$ , obtained by applying  $b$  to the same pairs of modes but reversing their order. However, this turns out not to give us any advantage.

<sup>6</sup>Indeed any orthogonal  $O$  with determinant  $-1$  can be written as  $O = b_{12}^{-1}O' = b_{12}O'$  for some  $O'$  of determinant 1.

From the claim, it follows easily that the representation is irreducible. Indeed, suppose the representation is reducible, so preserves a nontrivial subspace. Since our representation is unitary, this implies that our representation is decomposable; i.e., by a change of basis it can be brought into block-diagonal form.<sup>8</sup> In the new basis, the matrix consisting of 1's on the diagonal in the first block and 2's in the diagonal of the second block commutes with all elements of  $G$ , and in particular with  $R_1, R_2, R_3$ . But that matrix is not a multiple of the identity. Hence if only multiples of the identity commute with  $R_1, R_2, R_3$ , the representation must be irreducible.

We now prove the claim. First, since  $U$  commutes with  $R_1$ ,

$$\begin{pmatrix} A & D & G \\ B & E & H \\ C & F & I \end{pmatrix} \begin{pmatrix} \alpha^2 & \beta^* & \alpha\beta^* \\ \alpha\beta & -\alpha^* & |\beta|^2 \\ \beta & 0 & -\alpha^* \end{pmatrix} \\ = \begin{pmatrix} \alpha^2 & \beta^* & \alpha\beta^* \\ \alpha\beta & -\alpha^* & |\beta|^2 \\ \beta & 0 & -\alpha^* \end{pmatrix} \begin{pmatrix} A & D & G \\ B & E & H \\ C & F & I \end{pmatrix}.$$

This imposes nine equations. Below we give the equations coming from the (1,1), (1,2), (2,2), (2,3), and (3,2) entries of the above matrices, respectively.

$$(D\alpha + G)\beta = (C\alpha + B)\beta^*, \quad (1)$$

$$(A - E - F\alpha)\beta^* = D(\alpha^2 + \alpha^*), \quad (2)$$

$$B\beta^* = D\alpha\beta + F\beta\beta^*, \quad (3)$$

$$B\alpha\beta^* + E\beta\beta^* - H\alpha^* = G\alpha\beta - H\alpha^* + I\beta\beta^*, \quad (4)$$

$$C\beta^* = D\beta. \quad (5)$$

Note that Eqs. (5) and (1) imply that

$$G\beta = B\beta^*. \quad (6)$$

So by Eq. (4) we have

$$E\beta\beta^* = I\beta\beta^*. \quad (7)$$

So since  $0 < |\beta| < 1$ , we have  $I = E$ .

In total so far we have  $I = E$ ,  $G\beta = B\beta^*$ , and  $C\beta^* = D\beta$ . Next, since  $U$  commutes with  $R_2$ ,

$$\begin{pmatrix} A & D & G \\ B & E & H \\ C & F & E \end{pmatrix} \begin{pmatrix} \alpha & 0 & \beta^* \\ |\beta|^2 & \alpha & -\alpha^*\beta^* \\ -\alpha^*\beta & \beta & \alpha^{*2} \end{pmatrix} \\ = \begin{pmatrix} \alpha & 0 & \beta^* \\ |\beta|^2 & \alpha & -\alpha^*\beta^* \\ -\alpha^*\beta & \beta & \alpha^{*2} \end{pmatrix} \begin{pmatrix} A & D & G \\ B & E & H \\ C & F & E \end{pmatrix}.$$

<sup>8</sup>To see the equivalence of “reducible” and “decomposable” for unitary representations, it suffices to note that, if a set of unitary matrices always maps a subspace  $V$  to itself, then it cannot map any vector not in  $V$  to a vector in  $V$ , since this would violate unitarity.

This imposes another nine equations. Here are the equations from the (1,1), (2,1), and (2,2) entries, respectively, which we have simplified using  $I = E$ ,  $G\beta = B\beta^*$ , and  $C\beta^* = D\beta$ :

$$D\beta = D\beta\beta^* - G\alpha^*\beta, \quad (8)$$

$$E\beta\beta^* - H\alpha^*\beta = A\beta\beta^* - C\alpha^*\beta^*, \quad (9)$$

$$H\beta = D\beta\beta^* - F\alpha^*\beta^*. \quad (10)$$

Note that Eqs. (8) and (10), combined with the fact that  $G\beta = B\beta^*$ , imply that  $D\beta = H\beta$ , and hence  $D = H$ . Plugging this into Eq. (9), we see that  $E\beta\beta^* - D\alpha^*\beta = A\beta\beta^* - C\alpha^*\beta^*$ . Using  $C\beta^* = D\beta$  these last two terms cancel, so  $E\beta\beta^* = A\beta\beta^*$ , and hence  $E = A$ . So overall we have established that  $A = E = I$ ,  $D = H$ ,  $B = F$ ,  $G\beta = B\beta^*$ , and  $C\beta^* = D\beta$ .

Now suppose  $B = 0$ . Then we have from above that  $B = F = G = 0$ . By Eq. (8) we also have  $D\beta = D\beta\beta^* \Rightarrow D = 0$  since  $0 < |\beta| < 1$ . Hence we have  $C = 0$  as well by the fact that  $C\beta^* = D\beta$ . Therefore  $U$  is a multiple of the identity, as desired.

So it suffices to prove that  $B = 0$ . Suppose  $B \neq 0$ ; then we will derive a contradiction. Since  $U$  commutes with  $R_3$ ,

$$\begin{pmatrix} A & D & G \\ B & A & D \\ C & B & A \end{pmatrix} \begin{pmatrix} \alpha & \alpha\beta^* & \beta^{*2} \\ \beta & -|\alpha|^2 & -\alpha^*\beta^* \\ 0 & \beta & -\alpha^* \end{pmatrix} \\ = \begin{pmatrix} \alpha & \alpha\beta^* & \beta^{*2} \\ \beta & -|\alpha|^2 & -\alpha^*\beta^* \\ 0 & \beta & -\alpha^* \end{pmatrix} \begin{pmatrix} A & D & G \\ B & A & D \\ C & B & A \end{pmatrix}.$$

This imposes yet another nine equations, but we will only need the one coming from the (2,2) entry of the above matrices to complete the proof:

$$B\alpha\beta^* = -B\alpha^*\beta^*. \quad (11)$$

Since  $B \neq 0$ , Eq. (11) implies that  $\alpha = -\alpha^*$ ; i.e.,  $\alpha$  is pure imaginary. Furthermore, since  $G\beta = B\beta^*$ , we have  $G \neq 0$  as well. Using this, we can write out Eqs. (2) and (3) as follows:

$$(-B\alpha)\beta^* = D(\alpha^2 - \alpha) \Rightarrow G\beta = D(1 - \alpha), \quad (12)$$

$$B\beta^* = D\alpha\beta + F\beta\beta^* \Rightarrow G = D\alpha + G\beta. \quad (13)$$

Summing these equations, we see that  $G = D$ . Plugging back into equation (13), we see that  $\beta = 1 - \alpha$ . Since  $\alpha$  is pure imaginary this contradicts  $|\alpha|^2 + |\beta|^2 = 1$ .

To summarize, if  $U$  commutes with all elements of  $G$ , then  $U$  is a multiple of the identity. This proves the claim and hence the theorem. ■

We have learned that the set  $G_M$  forms a three-dimensional irreducible representation of  $G$ . We now leverage this fact, along with the classification of finite subgroups of  $SU(3)$ , to show that  $G$  is not finite.

*Claim 2.*  $G$  is infinite.

*Proof.* By Claim 1, if  $G$  is finite then  $\{R_1, R_2, R_3\}$  generates an irreducible representation of  $G$ . The finite subgroups of  $SU(3)$  consist of the finite subgroups of  $SU(2)$ , 12 exceptional finite subgroups, and two infinite families of “dihedral-like” groups, whose irreducible representations are classified in

[13–15]. Our proof proceeds by simply enumerating the possible finite groups that  $G$  could be, and showing that  $\{R_1, R_2, R_3\}$  cannot generate an irreducible representation of any of them.

First we eliminate the possibility that  $G$  is an exceptional finite subgroup of  $SU(3)$ . Of the 12 exceptional subgroups, only eight of them have three-dimensional irreps: they are labeled  $\Sigma(60)$ ,  $\Sigma(60) \times \mathbb{Z}_3$ ,  $\Sigma(168)$ ,  $\Sigma(168) \times \mathbb{Z}_3$ ,  $\Sigma(216)$ ,  $\Sigma(36 \times 3)$ ,  $\Sigma(216 \times 3)$ , and  $\Sigma(360 \times 3)$ . So by Claim 1, if  $G$  is finite and exceptional, then it is one of these eight groups.

The character tables of these groups are provided in [13] and [14]. Recall that the character of an element of a representation is the trace of its representative matrix. The traces of the matrices  $R_1, R_2, R_3$ , denoted  $T_1, T_2, T_3$ , are given by

$$T_1 = \alpha^2 - 2\alpha^*, \quad (14)$$

$$T_2 = (\alpha^*)^2 + 2\alpha, \quad (15)$$

$$T_3 = -|\alpha|^2 + \alpha - \alpha^* = -|\alpha|^2 + 2\text{Im}(\alpha). \quad (16)$$

We will show that these cannot be the characters of the elements of a three-dimensional irrep of  $\Sigma(60)$ ,  $\Sigma(60) \times \mathbb{Z}_3$ ,  $\Sigma(168)$ ,  $\Sigma(168) \times \mathbb{Z}_3$ ,  $\Sigma(216)$ ,  $\Sigma(36 \times 3)$ ,  $\Sigma(216 \times 3)$ , or  $\Sigma(360 \times 3)$ .

There are two three-dimensional irreps of  $\Sigma(60)$  up to conjugation [13]. The characters of their elements all lie in the set  $\{0, -1, 3, \frac{1+\sqrt{5}}{2}, \frac{1-\sqrt{5}}{2}\}$ . Note that  $0 < |\alpha|^2 < 1$ , which means that  $T_3$  cannot be in this set unless  $T_3 = \frac{1-\sqrt{5}}{2}$  and  $\text{Im}(\alpha) = 0$ . But then this implies  $\alpha = \pm\sqrt{\frac{\sqrt{5}-1}{2}}$ . Plugging this into  $T_1$  and  $T_2$ , we see they are not in the set of allowed values. Hence  $G$  is not  $\Sigma(60)$ .

The characters of the three-dimensional irreps of  $\Sigma(60) \times \mathbb{Z}_3$  are identical to those of  $\Sigma(60)$ , but with the additional possibility that they can be multiplied by  $e^{\frac{2\pi i}{3}}$  or  $e^{\frac{4\pi i}{3}}$ . The same argument as above shows that in order for  $T_3$  to be in the set of allowed characters, we must have  $\alpha = \pm\sqrt{\frac{\sqrt{5}-1}{2}}$  or  $\alpha = \frac{1+\sqrt{5}}{8}(\pm 1 \pm \sqrt{3}i)$ . Plugging these into  $T_1$ , we see the possible values of  $T_1$  are not in the set of allowed characters; hence  $G$  is not  $\Sigma(60) \times \mathbb{Z}_3$ .

There are two three-dimensional irreps of  $\Sigma(168)$  up to conjugation [13]. The characters of their elements all lie in the set  $S = \{0, \pm 1, 3, \frac{1}{2}(-1 \pm i\sqrt{7})\}$ . Since  $0 < |\alpha|^2 < 1$ , if  $T_3$  is in this set it must have value  $\frac{1}{2}(-1 \pm i\sqrt{7})$ . Therefore we must have  $\alpha = \pm\frac{1}{4} \pm \frac{\sqrt{7}}{4}i$ . This implies that  $\alpha^2 = \frac{-3}{8} \pm \frac{\sqrt{7}}{8}i$  and  $2\alpha^* = \pm\frac{1}{2} \pm \frac{\sqrt{7}}{2}i$ . Regardless of the signs chosen, this means that  $T_1$  is not in the set  $S$  of allowed values. Hence  $G$  is not  $\Sigma(168)$ .

The characters of the three-dimensional irreps of  $\Sigma(168) \times \mathbb{Z}_3$  are identical to those of  $\Sigma(168)$ , but with the additional possibility that they can be multiplied by  $e^{\frac{2\pi i}{3}}$  or  $e^{\frac{4\pi i}{3}}$ . The same argument as above shows that in order for  $T_3$  to be in the set of allowed characters, we must have  $\alpha = \pm\frac{1}{4} \pm \frac{\sqrt{7}}{4}i$ ,  $\alpha = \frac{1}{4}(\pm\sqrt{5} \pm i\sqrt{3})$ , or  $\alpha = \pm\frac{1}{4\sqrt{2}}\sqrt{7\sqrt{21}-13} \pm \frac{\sqrt{3+\sqrt{7}}}{8}i$ . Plugging these into  $T_1$ , we see that the possible values of  $T_1$  are not in the set of allowed characters; hence  $G$  is not  $\Sigma(168) \times \mathbb{Z}_3$ .

There is one three-dimensional irrep of  $\Sigma(216)$  up to conjugation [13]. The characters of its elements all lie in the set  $\{0, -1, 3\}$ . Since  $T_3$  cannot be in this set,  $G$  is not  $\Sigma(216)$ .

There are eight three-dimensional irreps of  $\Sigma(36 \times 3)$  up to conjugation [14]. The characters of their elements all lie in the set  $S = \{0, \pm 1, \pm e_3, \pm e_3^2, \pm e_4, \pm e_{12}^7, \pm e_{12}^{11}, \pm 3e_3, \pm 3e_3^2\}$ , where  $e_n = e^{\frac{2\pi i}{n}}$ . Since  $\text{Re}(T_3) = -|\alpha|^2$  and  $0 < |\alpha|^2 < 1$ , if  $T_3 \in S$  then we must have  $T_3 \in \{\pm e_3, \pm e_3^2, \pm e_{12}^7, \pm e_{12}^{11}\}$ . Solving for  $\alpha$  gives us  $\alpha \in \{\frac{\pm\sqrt{5}\pm\sqrt{3}i}{4}, \frac{\pm\sqrt{8\sqrt{3}-1}\pm i}{4}\}$ . A straightforward evaluation of possible values of  $T_1$  shows  $T_1 \notin S$ . So  $T_1$  and  $T_3$  cannot be characters of these irreps, and hence  $G$  is not  $\Sigma(36 \times 3)$ .

There are seven three-dimensional irreps of  $\Sigma(216 \times 3)$  up to conjugation [14]. The characters of their elements all lie in the set

$$S = \{0, \pm 1, 3, \pm e_3, \pm e_3^2, -e_9^2, -e_9^4, -e_9^5, -e_9^7, \pm e_9^2 + e_9^5, 2e_9^2 + e_9^5, -e_9^2 - 2e_9^5, e_9^4 + e_9^7, e_9^4 + 2e_9^7, -2e_9^4 - e_9^7\}.$$

If  $T_3 \in S$ , then for each case we can solve for  $\alpha$  and hence  $T_1$ . As above, a straightforward calculation shows that for no  $T_3 \in S$  do we have  $T_1 \in S$ . Hence  $G$  is not  $\Sigma(216 \times 3)$ .

There are four three-dimensional irreps of  $\Sigma(360 \times 3)$  up to conjugation [14]. The characters of their elements all lie in the set

$$S = \{0, \pm 1, \pm e_3, \pm e_3^2, 3e_3, 3e_3^2, -e_5 - e_5^4, -e_5^2 - e_5^3, -e_{15} - e_{15}^4, -e_{15}^7 - e_{15}^{13}, -e_{15}^{11} - e_{15}^{14}, -e_{15}^2 - e_{15}^8\}.$$

Again a straightforward calculation shows that for no  $T_3 \in S$  do we have  $T_1 \in S$ . Hence  $G$  is not  $\Sigma(360 \times 3)$ . We have therefore shown that  $G_M$  is not an irrep of an exceptional finite subgroup of  $SU(3)$ .

Next we will show that  $G_M$  is not in one of the two infinite families of “dihedral-like” finite subgroups of  $SU(3)$ , known as the  $C$ -series and the  $D$ -series groups. The most well-known members of these series are  $\Delta(3n^2)$  and  $\Delta(6n^2)$ , labeled by  $n \in \mathbb{N}$ , which consist of all  $3 \times 3$  even permutation matrices [for  $\Delta(3n^2)$ ] or all  $3 \times 3$  permutation matrices [for  $\Delta(6n^2)$ ] whose entries are replaced by  $n$ th roots of unity. In early works describing subgroups of  $SU(3)$ , such as Fairbairn, Fulton, and Klink [13], only  $\Delta(3n^2)$  and  $\Delta(6n^2)$  appear as elements of these series. However in 2011, Ludl [20] pointed out that there exist nontrivial subgroups of  $\Delta(3n^2)$  and  $\Delta(6n^2)$  which are missing from these references. Fortunately these groups have now been fully classified [21], and sufficient constraints have been placed on their representations [15] that we can eliminate the possibility that  $G$  is an irrep of any  $C$ - or  $D$ -series group.

In the following, we first eliminate the possibility that  $G_M$  is an irrep of  $\Delta(3n^2)$  or  $\Delta(6n^2)$  following the work of Fairbairn, Fulton, and Klink [13]. Afterwards we show that these arguments suffice to prove  $G_M$  is not an irrep of any of the  $C$ -series or  $D$ -series groups, using the work of Grimus and Ludl [15].

The three-dimensional irreps of  $\Delta(3n^2)$  are labeled by integers  $m_1, m_2 \in \{0, \dots, n-1\}$ , and have conjugacy classes labeled by types  $A, C, E$  and numbers  $p, q \in \{0, \dots, n-1\}$ . The respective characters are either 0 for conjugacy classes

$C(p, q)$  and  $E(p, q)$  or

$$e^{\frac{2\pi i}{n}(m_1 p + m_2 q)} + e^{\frac{2\pi i}{n}[m_1 q - m_2(p+q)]} + e^{\frac{2\pi i}{n}[-m_1(p+q) + m_2 p]} \quad (17)$$

for conjugacy class  $A(p, q)$ .

Assume that  $G_M$  is an irrep of  $\Delta(3n^2)$  for some  $n$ —we will derive a contradiction shortly. Then the trace of each  $R_i$  must be zero (if  $R_i$  is a representative of type  $C$  or  $E$ ) or of the form of Eq. (17) (if  $R_i$  is a representative of type  $A$ ). However, we can show that none of the traces  $T_i$  can be 0 because our beam splitter is nontrivial. Indeed  $T_3$  cannot be zero as  $0 < |\alpha|^2 < 1$ . We know that in order for  $T_1$  to be zero, we need  $\alpha^2 = 2\alpha^*$ , which implies  $|\alpha| = 2$  which is not possible, and likewise with  $T_2$ . Hence each  $T_i$  must have the form of Eq. (17), which implies each  $R_i$  is in conjugacy class  $A(p_i, q_i)$  for some choice of  $p_i, q_i$ . However, looking at the multiplication table for this group provided in [13, Table VIII], we have that  $A(p, q)A(p', q') = A(p + q \bmod n, p' + q' \bmod n)$ . Hence the  $T_i$ 's cannot possibly generate all of  $\Delta(3n^2)$  for any  $n$ , since they cannot generate elements in the conjugacy classes  $C(p, q)$  or  $E(p, q)$ . This contradicts our assumption that the  $R_i$ 's generate an irrep of  $\Delta(3n^2)$ . Therefore  $G_M$  is not an irrep of  $\Delta(3n^2)$  for any  $n$ .

We now extend this argument to eliminate the possibility that  $G_M$  is an irrep of any of the  $C$ -series groups. In Appendix E of [15], Grimus and Ludl show that for any three-dimensional irrep of a  $C$ -series group, there exists a basis (and an ordering of that basis) in which all elements of the  $A$  conjugacy classes are represented by diagonal matrices and  $E(0, 0)$  is represented by

$$\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}. \quad (18)$$

From this it can be easily shown that in any three-dimensional irrep of a  $C$ -series group, all elements of types  $C$  and  $E$  are represented by traceless matrices.<sup>9</sup> In our previous arguments eliminating  $\Delta(3n^2)$  as a possibility, we showed that none of the generators  $R_i$  can be traceless, so each of the  $R_i$  must be of type  $A$ . Again this is a contradiction since elements of type  $A$  generate an Abelian group and  $G_M$  is non-Abelian. Hence  $G_M$  cannot be an irrep of one of the  $C$ -series groups.

Next we turn our attention to the  $D$ -series finite subgroups of  $SU(3)$ . We begin by showing that  $G_M$  cannot be an irrep of  $\Delta(6n^2)$  for any  $n$ , and we will later generalize this to eliminate all  $D$ -series groups as possibilities. The group  $\Delta(6n^2)$  contains 6 families of conjugacy classes, labeled by types  $A, B, C, D, E, F$  and by integers  $p, q$  as above. The three-dimensional irreps of  $\Delta(6n^2)$  are again labeled by  $(m_1, m_2)$ , which now take values in  $(m, 0), (0, m)$ , or  $(m, m)$ , as well as

$t \in \{0, 1\}$ . The character of each element is

$$\begin{aligned} \text{Tr}[A(p, q)] &= e^{\frac{2\pi i}{n}(m_1 p + m_2 q)} + e^{\frac{2\pi i}{n}[m_1 q - m_2(p+q)]} \\ &\quad + e^{\frac{2\pi i}{n}[-m_1(p+q) + m_2 p]}, \end{aligned} \quad (19)$$

$$\text{Tr}[B(p, q)] = (-1)^t e^{\frac{2\pi i}{n}(m_1 p + m_2 q)}, \quad (20)$$

$$\text{Tr}[D(p, q)] = (-1)^t e^{\frac{2\pi i}{n}[m_1(\frac{n}{2} - p - q) + m_2 p]}, \quad (21)$$

$$\text{Tr}[F(p, q)] = (-1)^t e^{\frac{2\pi i}{n}[m_1 q + m_2(\frac{n}{2} - p - q)]}, \quad (22)$$

$$\text{Tr}[C(p, q)] = \text{Tr}[E(p, q)] = 0. \quad (23)$$

We now eliminate the possibility that  $G_M$  is an irrep of  $\Delta(6n^2)$  for any  $n$ . Again assume by way of contradiction that  $G_M$  is an irrep of  $\Delta(6n^2)$  for some  $n$ . Then each  $R_i$  must be in one of the types  $A, B, C, D, E, F$ , and each trace  $T_i$  must have the corresponding character from Eqs. (19)–(23). As noted previously each  $T_i$  cannot be 0, so in fact each  $R_i$  must be of types  $A, B, D$ , or  $F$ . Furthermore, we will show the following lemma:

**Lemma 1.** If  $G_M$  is an irrep of  $\Delta(6n^2)$ , then all  $R_i$  of types  $B, D$  or  $F$  are of the same type.

By Lemma 1, some of the  $R_i$ 's belong to a single type  $B, D$  or  $F$  while the remaining  $R_i$ 's are of type  $A$ . However, by examining the multiplication table for this group provided in [13, Table VIII], one can see that any number of elements of type  $A$  plus any number of elements from a single type  $B, D$ , or  $F$  cannot generate the entire group. This contradicts our assumption that the  $R_i$ 's generate an irrep of  $\Delta(6n^2)$ . Hence  $G_M$  is not an irrep of  $\Delta(6n^2)$  so  $G$  cannot be  $\Delta(6n^2)$  by Claim 1. We now prove Lemma 1 before continuing the proof of Claim 2.

**Proof of Lemma 1.** Assume that  $G_M$  is an irrep of  $\Delta(6n^2)$ . We will show that all of the  $R_i$ 's of types  $B, D$  or  $F$  are of the same type. We proceed by enumerating all pairs  $R_i, R_j$  for  $i \neq j$  and show that it is not possible for  $R_i$  and  $R_j$  to be of distinct types  $B, D$ , or  $F$ .

Let  $\alpha = a + bi$  where  $a$  and  $b$  are real. If  $R_i$  is of type  $B, D$ , or  $F$ , then  $T_i$  has norm 1, which imposes the following equations on  $a$  and  $b$ :

$$|T_1|^2 = 1 \Rightarrow (a^2 + b^2)^2 + 4[a^2(1 - a) + b^2(3 + a)] = 1, \quad (24)$$

$$|T_2|^2 = 1 \Rightarrow (a^2 + b^2)^2 + 4[a^2(1 + a) + b^2(1 - 3a)] = 1, \quad (25)$$

$$|T_3|^2 = 1 \Rightarrow (a^2 + b^2)^2 + 4b^2 = 1. \quad (26)$$

First suppose that  $R_1$  and  $R_2$  are members of distinct types  $B, D$ , or  $F$ . Then  $|T_1| = |T_2| = 1$ . The only solutions to Eqs. (24) and (25) in which  $0 < |\alpha|^2 = a^2 + b^2 < 1$  are  $(a = 0, b = \pm\sqrt{\sqrt{5}-2})$  and  $(a = \pm\frac{1}{2}\sqrt{3(\sqrt{5}-2)}, b = \pm\frac{1}{2}\sqrt{\sqrt{5}-2})$ . Note also that the product  $R_1 R_2$  must be of type  $C$  or  $E$  according to the group multiplication table in [13, Table VIII]. Hence the trace of  $R_1 R_2$  must be 0 if  $G_M$  is an

<sup>9</sup>To see this, note that by the group multiplication table in [13, Table VIII], we have that  $A(p, q) = E(p, q)E(0, 0)E(0, 0)$ , so  $A(p, q)$  is in a  $D$ -series group if and only if  $E(p, q)$  is in the group. Additionally, since  $A(p, q)E(0, 0) = E(p, q)$ , all elements of type  $E$  are obtainable by multiplying an element of type  $A$  by  $E(0, 0)$ . Since in this basis the  $A$  matrices are diagonal, and  $E(0, 0)$  is represented by the above matrix (18), this implies the claim for elements of type  $E$ . A similar argument holds for the elements of type  $C$ .

irrep of  $\Delta(6n^2)$ . This implies that

$$\text{Tr}(R_1 R_2) = \alpha^3 - \alpha^{*3} + |\beta|^2(1 + \beta + \beta^* - |\alpha|^2) - |\alpha|^2 = 0. \quad (27)$$

Since we have  $\alpha = a + bi$  where the values of  $a$  and  $b$  are one of the six possibilities above, one can see that there is no  $\beta$  which satisfies Eq. (27). Indeed, note that  $\alpha^3 - \alpha^{*3}$  is nonzero and pure imaginary, while the rest of the expression is real, so the terms in Eq. (27) cannot sum to zero. This provides the desired contradiction. We conclude that  $R_1$  and  $R_2$  cannot be of distinct types  $B$ ,  $D$ , or  $F$ .

Next suppose that  $R_1$  and  $R_3$  are of distinct types  $B$ ,  $D$ , or  $F$ . Then  $|T_1| = |T_3| = 1$ . If  $\alpha = a + bi$  as before, Eqs. (24) and (26), combined with the fact that  $0 < |\alpha|^2 = a^2 + b^2 < 1$ , imply that  $a = 0$  and  $b = \pm\sqrt{\sqrt{5}-2}$ . Again, using the group multiplication table in [13, Table VIII] we must have that  $R_1 R_3$  is of type  $C$  or  $E$  so

$$\text{Tr}(R_1 R_3) = \alpha^3 + \alpha^*|\alpha|^2 + \alpha^{*2} + |\beta|^2(1 + \beta + \beta^* + \alpha^2) = 0. \quad (28)$$

Since  $\alpha = \pm i\sqrt{\sqrt{5}-2}$ , this is a contradiction—for the terms  $\alpha^3 + \alpha^*|\alpha|^2$  of Eq. (28) are nonzero and pure imaginary while the remaining terms are real. Hence  $R_1$  and  $R_3$  cannot be of distinct types  $B$ ,  $D$ , or  $F$ .

Finally suppose that  $R_2$  and  $R_3$  are of distinct types  $B$ ,  $D$ , or  $F$ . Then  $|T_2| = |T_3| = 1$ . If  $\alpha = a + bi$  then the only solutions to Eqs. (25) and (26) in which  $0 < |\alpha|^2 = a^2 + b^2 < 1$  are  $(a = 0, b = \pm\sqrt{\sqrt{5}-2})$  and  $(a \approx 0.437668, b \approx \pm 0.457975)$ . Furthermore using the group multiplication table in [13, Table VIII] we must have that  $R_2 R_3$  is of type  $C$  or  $E$  so

$$\text{Tr}(R_2 R_3) = \alpha^2 - \alpha^{*3} - \alpha|\alpha|^2 + |\beta|^2(\alpha\beta^* - \alpha^*\beta^* - 2\alpha^*) = 0. \quad (29)$$

With slightly more work, one can again check that Eq. (29) cannot be satisfied with the above values of  $\alpha$ , under the additional constraint that  $|\alpha|^2 + |\beta|^2 = 1$ , providing the desired contradiction. Hence  $R_2$  and  $R_3$  cannot be of distinct types  $B$ ,  $D$ , or  $F$ , which completes the proof of Lemma 1. ■

We have therefore eliminated the possibility that  $G_M$  is an irrep of  $\Delta(6n^2)$  for any  $n$ , and so  $G \neq \Delta(6n^2)$  by Claim 1. We now extend this argument to eliminate the possibility that  $G_M$  is an irrep of any of the  $D$ -series groups. In Appendix G of [15], Grimus and Ludl show that for any three-dimensional irrep of a  $D$ -series group, there exists a basis (and an ordering of that basis) in which all elements of the  $A$  conjugacy classes are represented by diagonal matrices, and  $E(0,0)$  and  $B(0,0)$  are represented by

$$E(0,0) \rightarrow \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \quad B(0,0) \rightarrow \pm \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}. \quad (30)$$

From this it can be easily shown that in any three-dimensional irrep of a  $D$ -series group, all elements of types  $C$  and  $E$  are represented by traceless matrices, and all elements of types  $B$ ,  $D$ , and  $F$  are represented by matrices whose trace has

unit norm.<sup>10</sup> In our previous arguments eliminating  $\Delta(6n^2)$  as a possibility, we showed none of our generators  $R_i$  can be traceless, and those of trace norm 1 are of the same type. Hence some of our generators are of type  $A$  and the remainder are of a single type  $B$ ,  $D$  or  $F$ . Again this is a contradiction since any number of elements of type  $A$  and any number of elements of a single type  $B$ ,  $D$  or  $F$  do not suffice to generate any  $D$ -series group—in particular they cannot generate  $E(0,0)$ . Hence  $G_M$  cannot be an irrep of any of the  $D$ -series groups. This concludes the proof that  $G_M$  cannot be an irrep of any of the dihedral-like subgroups of  $SU(3)$ .

Finally we will show that  $G$  is not a finite subgroup of  $SU(2)$ . Since  $SU(2)$  is a double cover of  $SO(3)$ , if  $G$  is a finite subgroup of  $SU(2)$ , then  $G$  must be either a finite subgroup of  $SO(3)$  or else the double cover of such a subgroup. We first eliminate the finite subgroups of  $SO(3)$ . The dihedral and cyclic subgroups have no three-dimensional irreps; hence  $G$  cannot be one of these by Claim 1. The icosahedral subgroup is isomorphic to  $\Sigma(60)$  so has already been eliminated. The octahedral and tetrahedral subgroups do have three-dimensional irreps. However, the characters of their elements all lie in the set  $\{0, \pm 1, \pm 3\}$ , so these can be eliminated just as the exceptional groups of  $SU(3)$  were eliminated.

Now all that remains are double covers of the finite subgroups of  $SO(3)$ . The binary dihedral groups, also known as the dicyclic groups, have no three-dimensional irreps, so  $G$  cannot be a binary dihedral group by Claim 1. The binary tetrahedral group has one three-dimensional irrep, with character values in the set  $\{0, \pm 1, \pm 3\}$ . So  $T_3$  cannot be in this set as noted above.

The binary octahedral group has two three-dimensional irreps, with character values also in  $\{0, \pm 1, \pm 3\}$ , so is likewise eliminated. The binary icosahedral group has two three-dimensional irreps, with all characters in the set  $\{0, -1, 3, \frac{\sqrt{5} \pm 1}{2}\}$ . As discussed in the case of  $\Sigma(60)$ , our traces cannot take these values.

In summary, by enumeration of the finite subgroups of  $SU(3)$ , we have shown that  $G$  cannot be finite. ■

*Corollary 2.*  $G$  is a continuous (Lie) subgroup of  $SU(3)$ .

*Proof.*  $G$  is infinite by Claim 2. Furthermore  $G$  is closed because it is the set of matrices *densely* generated by  $\{R_1, R_2, R_3\}$ . It is well known that a closed, infinite subgroup of a Lie group is also a Lie group (this is Cartan's theorem [22]). The corollary follows. ■

Next we show that  $G$  must be either  $SO(3)$ ,  $SU(2)$ , or  $SU(3)$ . Furthermore, the set of matrices  $G_M$  densely generated by  $\{R_1, R_2, R_3\}$  consists of either all  $SO(3)$  matrices or all  $SU(3)$  matrices.

<sup>10</sup>The fact that matrices representing elements of types  $C$  and  $E$  are traceless follows from the previous arguments regarding  $C$ -series groups. The fact that matrices representing elements of types  $B$ ,  $D$ , and  $F$  have traces of norm 1 follows by an identical argument since  $A(p,q) = B(p,q)B(0,0)$ ,  $A(p,q)B(0,0) = B(p,q)$ ,  $A$  matrices have diagonal representatives, and  $B(0,0)$  is represented by the above in this basis. A similar argument holds for elements of types  $D$  and  $F$ .

*Claim 3.*  $G$  is either  $\text{SO}(3)$ ,  $\text{SU}(2)$ , or  $\text{SU}(3)$ . Furthermore,  $G_M$  consists of either all  $3 \times 3$  special unitary matrices (if the beam splitter  $b$  has a nonreal entry), or all  $3 \times 3$  special orthogonal matrices (if  $b$  is real).

*Proof.* Since  $R_1$ ,  $R_2$ , and  $R_3$  do not commute,  $G$  is non-Abelian. By Corollary 2, we know  $G$  is a Lie group, and furthermore  $G$  is closed. The non-Abelian closed connected Lie subgroups of  $\text{SU}(3)$  are well known [23]: they are  $\text{SU}(3)$ ,  $\text{SU}(2) \times U(1)$ ,  $\text{SU}(2)$ , and  $\text{SO}(3)$ . Meanwhile, the closed disconnected Lie subgroups of  $\text{SU}(3)$  are  $\Delta(3\infty)$  and  $\Delta(6\infty)$ , as described in [13].

Note that  $\Delta(3\infty)$  and  $\Delta(6\infty)$  are the analogs of  $\Delta(3n^2)$  and  $\Delta(6n^2)$  as  $n \rightarrow \infty$ . Our above arguments showing that  $G \neq \Delta(3n^2)$  and  $G \neq \Delta(6n^2)$  carry over in this limit, because at no point did we use the fact that  $n$  or  $m$  were finite. Therefore  $G$  cannot be either of these continuous groups.

By Claim 1,  $G$  has a three-dimensional irrep. Of the remaining groups, only  $\text{SU}(2)$ ,  $\text{SO}(3)$ , and  $\text{SU}(3)$  have three-dimensional irreps. Furthermore, it is well known that the only three-dimensional irrep of  $\text{SU}(2)$  is as  $\text{SO}(3)$ . This is because  $\text{SU}(2)$  has exactly one irrep in each finite dimension (see [23, Sec. II.5] or [24] for details), and  $\text{SU}(2)$  has an obvious representation as  $\text{SO}(3)$  via the fact that  $\text{SU}(2)$  is a double cover of  $\text{SO}(3)$ . Since we are only concerned with the set of matrices  $G_M$  generated, without loss of generality we can assume  $G$  is either  $\text{SO}(3)$  or  $\text{SU}(3)$ .

It is well known that the only three-dimensional irrep of  $\text{SU}(3)$  is the natural one, as the group of all  $3 \times 3$  special unitary matrices ([23, Sec. VI.5]). Likewise, the only three-dimensional irrep of  $\text{SO}(3)$  is the natural one, up to conjugation by a unitary [23]. Hence  $G_M$  consists of either all  $3 \times 3$  special unitary matrices (case A), or all  $3 \times 3$  special orthogonal matrices conjugated by some unitary  $U$  (case B).

We now show that if the beam splitter  $b$  is real, then we are in case B and without loss of generality the conjugating unitary  $U$  is real. Hence  $G_M$  is the set of all  $3 \times 3$  orthogonal matrices. Otherwise, if  $b$  has a complex entry, we will show we are in case A and  $G_M$  is the set of all  $3 \times 3$  special unitary matrices.

First, suppose  $b$  is real. Then all matrices in our generating set are orthogonal, so all matrices in  $G_M$  are orthogonal. Hence we are in case B, and since all matrices in  $G_M$  are real, without loss of generality  $U$  is a real matrix as well.

Now suppose that  $b$  has a complex entry. Then either  $\alpha$  or  $\beta$  are not real. First, suppose  $\alpha$  is not real. Then  $\text{Tr}(R_1) = \alpha^2 - 2\alpha^*$  is not real because  $0 < |\alpha| < 1$ . But since conjugating a matrix by a unitary preserves its trace, and we are in case B, the traces of all matrices in  $G_M$  must be real. In particular  $\text{Tr}(R_1)$  must be real, which is a contradiction. Therefore if  $\alpha$  is not real then we must be in case A.

Next, suppose  $\beta$  is not real. Then we can obtain a similar contradiction. Let  $\beta = p + qi$  where  $p$  and  $q$  are real. By direct calculation one can show that  $\text{Im}[\text{Tr}(R_1 R_2 R_3 R_1)] = |\beta|^4(\beta^{*2} + 2\beta)$ . Since our beam splitter is nontrivial,  $|\beta|^4 \neq 0$ , so this quantity is 0 if and only if  $\beta^{*2} + 2\beta = 0 \Leftrightarrow 2q(1 - p) = 0$ . But this cannot occur, since  $q \neq 0$  (because  $\beta$  is not real), and  $1 - p \neq 0$  (because the beam splitter is nontrivial). Hence in this case  $\text{Tr}(R_1 R_2 R_3 R_1)$  is imaginary, which contradicts the fact we are in case B. Therefore if  $\beta$  is not real then we must be in case A, which completes the proof. ■

Theorem 1 follows from Claim 3. Having proved our main result, we can now easily show two alternative versions of the theorem as well.

*Corollary 3.* Any nontrivial two-mode optical gate  $g = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$  (not necessarily of determinant  $-1$ ), plus the set of all phase shifters, densely generates  $\text{SU}(m)$  on  $m \geq 3$  modes.

*Proof.* Since  $g$  is unitary we have  $\det(g) = e^{i\theta}$  for some  $\theta$ . By composing  $g$  with a phase of  $e^{i\frac{\pi-\theta}{2}}$ , we obtain a nontrivial beam splitter  $g'$  of determinant  $-1$ . The gate  $g'$  is universal by Theorem 1; hence this gate set is universal as well. ■

*Corollary 4.* Any nontrivial two-mode real optical gate  $g$  is universal for quantum linear optics.

*Proof.* Since  $g$  is real,  $g$  must have determinant  $\pm 1$ . The case of  $\det(g) = -1$  is handled by Theorem 1, so we now prove the  $\det(g) = +1$  case. In this case  $g$  is a rotation by an angle  $\theta$ . The fact that  $g$  is nontrivial means  $\theta$  is not a multiple of  $\pi/2$ . The beam splitter actions  $b_{12}, b_{23}, b_{13}$  can be viewed as three-dimensional rotations by angle  $\theta$  about the  $x$ ,  $y$ , and  $z$  axes. So the question reduces to “For which angles  $\theta$  (other than multiples of  $\pi/2$ ) do rotations by  $\theta$  about the  $x$ ,  $y$ , and  $z$  axes fail to densely generate all possible rotations?”

This question is easily answered using the well known classification of closed subgroups of  $\text{SO}(3)$ . The finite subgroups of  $\text{SO}(3)$  are the cyclic, dihedral, tetrahedral, octahedral, and icosahedral groups. One can easily check that our gate  $g$  cannot generate a representation of one of these groups, and hence densely generates some infinite group  $G$ . By the same reasoning as in Corollary 2, we conclude that  $G$  is a Lie subgroup of  $\text{SO}(3)$ .

The Lie subgroups of  $\text{SO}(3)$  are  $\text{SO}(3)$ ,  $U(1)$  (all rotations about one axis), and  $U(1) \times \mathbb{Z}_2$  (all rotations about one axis, plus a rotation by  $\pi$  perpendicular to the axis). Again one can easily eliminate the possibility that  $G$  is  $U(1)$  or  $U(1) \times \mathbb{Z}_2$ , and hence  $G$  must be all of  $\text{SO}(3)$ .

We have proven universality on three modes for real nontrivial  $g$  with determinant  $+1$ . Universality on  $m \geq 3$  modes follows by a real analog of Reck *et al.* [12], namely that any rotation matrix in  $\text{SO}(m)$  can be expressed as the product of  $O(m^2)$  real  $2 \times 2$  optical gates of determinant 1. ■

#### IV. OPEN QUESTIONS

At the moment our dichotomy theorem only holds for beam splitters, which act on two modes at a time and have determinant  $-1$ . As we said before, we leave open whether the dichotomy can be extended to two-mode gates with determinant other than  $-1$ . Although the phases of gates are irrelevant in the qubit model, the phases unfortunately *are* relevant in linear optics—and that is the source of the difficulty. Note that the previous universality result of Reck *et al.* [12] simply assumed that arbitrary phase shifters were available for free, so this issue did not arise.

Another open problem is whether our dichotomy can be extended to  $k$ -mode optical gates for all constants  $k$ . Such a result would complete the linear-optical analog of the dichotomy conjecture for standard quantum circuits. The case  $k = 3$  seems doable because the representations of all exceptional finite subgroups of  $\text{SU}(4)$  are known [25]. But already the case  $k = 4$  seems more difficult, because the representations of all finite subgroups of  $\text{SU}(5)$  have not yet

been classified. Thus, a proof for arbitrary  $k$  would probably require more advanced techniques in representation theory.

### ACKNOWLEDGMENTS

We thank Bela Bauer for pointing out Ref. [20] and Patrick Otto Ludl for helpful correspondence. A.B. was supported by

the National Science Foundation Graduate Research Fellowship under Grant No. 1122374 and by the Center for Science of Information (CSoI), an NSF Science and Technology Center, under Grant Agreement No. CCF-0939370. S.A. was supported by the National Science Foundation under Grant No. 0844626, by a TIBCO Chair, and by an Alan T. Waterman Award.

- 
- [1] E. Knill and R. Laflamme, *Phys. Rev. Lett.* **81**, 5672 (1998).
  - [2] M. Bremner, R. Jozsa, and D. Shepherd, *Proc. R. Soc. London A* **467**, 459 (2010).
  - [3] S. Aaronson and A. Arkhipov, *Theory of Computing* **9**, 143 (2013).
  - [4] S. Lloyd, *Phys. Rev. Lett.* **75**, 346 (1995).
  - [5] Y. Shi, *Quantum Inf. Comput.* **3**, 084 (2003).
  - [6] D. Gottesman, in S. P. Corney, R. Delbourgo, and P. D. Jarvis, editors, *Group22: Proceedings of the XXII International Colloquium on Group Theoretical Methods in Physics*, Vol. 1 (International Press, Cambridge, MA, 1999), pp. 32–43.
  - [7] R. Jozsa and M. V. Nest, *Quantum Inf. Comput.* **14**, 0633 (2014).
  - [8] S. P. Jordan, *Quantum Inf. Comput.* **10**, 0470 (2010).
  - [9] M. Nielsen and I. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, 2000).
  - [10] E. Knill, R. Laflamme, and G. J. Milburn, *Nature (London)* **409**, 46 (2001).
  - [11] N. J. Cerf, C. Adami, and P. G. Kwiat, *Phys. Rev. A* **57**, R1477 (1998).
  - [12] M. Reck, A. Zeilinger, H. J. Bernstein, and P. Bertani, *Phys. Rev. Lett.* **73**, 58 (1994).
  - [13] W. M. Fairbairn, T. Fulton, and W. H. Klink, *J. Math. Phys.* **5**, 1038 (1964).
  - [14] A. Hanany and Y.-H. He, *J. High Energy Phys.* 02 (1999) 013.
  - [15] W. Grimus and P. O. Ludl, *J. Phys. A: Math. Theor.* **45**, 233001 (2012).
  - [16] S. D. Bartlett and B. C. Sanders, *J. Mod. Opt.* **50**, 2331 (2003).
  - [17] See <http://www.scottaaronson.com/blog/?p=1579>.
  - [18] D. Gottesman, A. Kitaev, and J. Preskill, *Phys. Rev. A* **64**, 012310 (2001).
  - [19] C. Dawson and M. Nielsen, *Quantum Inf. Comput.* **6**, 081 (2006).
  - [20] P. O. Ludl, *J. Phys. A: Math. Theor.* **44**, 255204 (2011).
  - [21] W. Grimus and P. O. Ludl, *J. Phys. A: Math. Theor.* **47**, 075202 (2014).
  - [22] É. Cartan, La théorie des groupes finis et continus et l'analysis situs, *Mémoires des Sciences Mathématiques* **42**, 1 (1952).
  - [23] T. Bröcker and T. tom Dieck, *Representations of Compact Lie Groups* (Springer, Berlin, 2003).
  - [24] Q. Yuan, <http://qchu.wordpress.com/2011/06/26/the-representation-theory-of-su2>.
  - [25] A. Hanany and Y.-H. He, *J. High Energy Phys.* 02 (2001) 027.