Multipartite States Under Local Unitary Transformations

S. Albeverio, L. Cattaneo, S.-M. Fei, X.-H. Wang

no. 209

Diese Arbeit ist mit Unterstützung des von der Deutschen Forschungsgemeinschaft getragenen Sonderforschungsbereiches 611 an der Universität Bonn entstanden und als Manuskript vervielfältigt worden.

Bonn, Januar 2005
Multipartite states under local unitary transformations

Sergio Albeverio\textsuperscript{a} \textsuperscript{1}, Laura Cattaneo\textsuperscript{a} \textsuperscript{2}, Shao-Ming Fei\textsuperscript{a} \textsuperscript{b} \textsuperscript{3}, Xiao-Hong Wang\textsuperscript{b} \textsuperscript{4}

\textsuperscript{a} Institut für Angewandte Mathematik, Universität Bonn, D-53115 Bonn
\textsuperscript{b} Department of Mathematics, Capital Normal University, Beijing 100037

Abstract

The equivalence problem under local unitary transformation for \(n\)-partite pure states is reduced to the one for \((n-1)\)-partite mixed states. In particular, a tripartite system \(\mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C\), where \(\mathcal{H}_j\) is a finite dimensional complex Hilbert space for \(j = A, B, C\), is considered and a set of invariants under local transformations is introduced, which is complete for the set of states whose partial trace with respect to \(\mathcal{H}_A\) belongs to the class of generic mixed states.

Introduction

The importance of a measure to quantify entanglement became evident in the years by the number of applications exploiting nonlocality properties which have been developed: we mention, among others, quantum computation (see, e.g., [1, 2]), quantum teleportation (see, e.g., [3, 4, 5, 6, 7, 8, 9, 10]), superdense coding (see, e.g., [11]), quantum cryptography (see, e.g., [12, 13, 14]).

Many proposals have been made for a measure of entanglement in the bipartite case, see e.g., [15, 16, 17, 18, 19, 20, 21, 22]. Less results are known instead for the tripartite and in general for the \(n\)-partite case [20, 23, 24, 25], although such systems are important for example in quantum multiparticle teleportation or teleporting processes.

One of the properties employed in the bipartite case is the Schmidt-decomposition [26]. However this decomposition is a peculiarity of bipartite systems and does not exist for \(n\)-partite ones, a sign of the complexity of the many-partite problem. Generalizations of the Schmidt-decomposition have been proposed [27, 28, 29, 30], but the results are not sufficient to provide good measures of entanglement in the \(n\)-partite case. In the following, we first reduce the \(n\)-partite problem to a \((n-1)\)-partite one. To illustrate this, we consider the case of a tripartite system. Then we define invariants under local unitary transformations which form a complete set at least for tripartite states for which a solution of the bipartite problem for entanglement measures is known.

\footnote{SFB 611; IZKS; BiBoS; CERFIM (Locarno); Acc. Arch. USI (Mendrisio)
e-mail: albeverio@uni-bonn.de}
\footnote{e-mail: cattaneo@wiener.iam.uni-bonn.de}
\footnote{e-mail: fei@uni-bonn.de}
\footnote{e-mail: wangsh@mail.cnu.edu.cn}

1

1
Tripartite states as bipartite ones

Let $\mathcal{H}_A$, $\mathcal{H}_B$, and $\mathcal{H}_C$ be complex Hilbert spaces of finite dimension $N_A$, $N_B$, and $N_C$, respectively, and let $\{|j\rangle_k\}_{j=1}^{N_k}$, $k = A, B, C$, be an orthonormal basis of $\mathcal{H}_k$. A pure state $|\psi\rangle$ in $\mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$ can then be written as

$$|\psi\rangle = \sum_{j=1}^{N_A} \sum_{k=1}^{N_B} \sum_{l=1}^{N_C} a_{jkl}|j\rangle_A \otimes |k\rangle_B \otimes |l\rangle_C , \quad \sum_{j=1}^{N_A} \sum_{k=1}^{N_B} \sum_{l=1}^{N_C} a_{jkl}^* a_{jkl} = 1.$$  

We denote by $U(\mathcal{H})$ the group of all unitary operators on the space $\mathcal{H}$.

First of all, we can consider tripartite states as special cases of bipartite ones, by decomposing the system into two subsystems, for example $A-BC$. The following lemma holds.

**Lemma 1** Let $|\psi\rangle$, $|\psi'\rangle$ be two pure states in $\mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$ and define $\rho = \text{Tr}_A(|\psi\rangle\langle\psi|)$, $\rho' = \text{Tr}_A(|\psi'\rangle\langle\psi'|)$, where $\text{Tr}_A$ denotes the partial trace with respect to $\mathcal{H}_A$.

1. The function $I^A_\alpha(|\psi\rangle) = \text{Tr}\rho^\alpha$ is invariant under local unitary transformations, for any $\alpha \in \mathbb{N}$;

2. If $I^A_\alpha(|\psi\rangle) = I^A_\alpha(|\psi'\rangle)$ for $\alpha = 1, \ldots, \min\{N_A, N_B \cdot N_C\}$, there exist $U_A \in U(\mathcal{H}_A)$, $U_{BC} \in U(\mathcal{H}_B \otimes \mathcal{H}_C)$ such that $|\psi'\rangle = U_A \otimes U_{BC}|\psi\rangle$. In particular, $\rho' = U_{BC} \rho U_{BC}^\dagger$.

**Proof.** As already shown in [25], a) is easily proved as $\text{Tr}_A(|\psi\rangle\langle\psi|) = A_A^T A_A^*$, where $A_A$ is the matrix obtained considering $|\psi\rangle$ as a bipartite state in the $A-BC$ system, with the row (resp. column) indices from the subsystem $A$ (resp. $BC$). The indices $^T$ resp. $^*$ denote transpose resp. complex conjugation. As an example,

$$A_A = \begin{pmatrix} a_{111} & a_{112} & a_{121} & a_{122} \\ a_{211} & a_{212} & a_{221} & a_{222} \end{pmatrix}$$

is the matrix $A_A$ for the case $N_A = N_B = N_C = 2$. Indeed, if $|\psi'\rangle = U_A \otimes U_B \otimes U_C |\psi\rangle$, with $U_i \in U(\mathcal{H}_i)$, $i = A, B, C$, then $A_A'$ and $A_A$ are related by

$$A_A' = U_A A_A (U_B \otimes U_C)^T$$

and

$$I^A_\alpha(|\psi'\rangle) = \text{Tr}(A_A'^T A_A'^*)^\alpha = \text{Tr}((U_A A_A (U_B \otimes U_C)^T)^T (U_A A_A (U_B \otimes U_C)^T)^*)^\alpha$$

$$= \text{Tr}(U_B \otimes U_C (A_A^T A_A^*)^\alpha (U_B \otimes U_C)^\dagger) = \text{Tr}(A_A^T A_A^*)^\alpha$$

$$= I^A_\alpha(|\psi\rangle)$$

for any power $\alpha \in \mathbb{N}$. The decomposition $|\psi'\rangle = U_A \otimes U_{BC} |\psi\rangle$ follows directly considering $|\psi\rangle$ as a bipartite state of the system $A-BC$ and applying the results of [21]. \endproof

**Remark.** The statement can be generalized to $n$-partite systems: the equivalence problem for $n$-partite pure states is reduced in this way to the equivalence problem for $(n-1)$-partite mixed states.
Reduction to bipartite mixed states

Lemma 1 allows us to reduce the tripartite problem on $\mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$ to a bipartite problem on $\mathcal{H}_B \otimes \mathcal{H}_C$.

**Lemma 2** Let $|\psi^\prime\rangle = U_A \otimes U_{BC} |\psi\rangle$, with $U_A \in U(\mathcal{H}_A)$, $U_{BC} \in U(\mathcal{H}_B \otimes \mathcal{H}_C)$ and define $\rho = \text{Tr}_A (|\psi\rangle\langle\psi|)$, $\rho^\prime = \text{Tr}_A (|\psi^\prime\rangle\langle\psi^\prime|)$. If

$$\rho^\prime = U_B \otimes U_C \rho U_B^\dagger \otimes U_C^\dagger,$$

where $U_B \in U(\mathcal{H}_B)$ and $U_C \in U(\mathcal{H}_C)$, then there exist matrices $V_A \in U(\mathcal{H}_A)$, $V_B \in U(\mathcal{H}_B)$, $V_C \in U(\mathcal{H}_C)$ such that

$$|\psi^\prime\rangle = V_A \otimes V_B \otimes V_C |\psi\rangle,$$

i.e., $|\psi\rangle$ and $|\psi^\prime\rangle$ are equivalent under local unitary transformations.

**Proof.** On one hand we have

$$U_{BC} \text{Tr}_A (|\psi\rangle\langle\psi|)^a U_{BC}^\dagger = \text{Tr}_A \left((1 \otimes U_{BC} |\psi\rangle\langle\psi| (1 \otimes U_{BC})^\dagger)^a \right)$$

$$= \text{Tr}_A \left(U_A \otimes U_{BC} |\psi\rangle\langle\psi| (U_A \otimes U_{BC})^\dagger)^a \right),$$

on the other hand

$$U_B \otimes U_C \text{Tr}_A (|\psi\rangle\langle\psi|)^a U_B^\dagger \otimes U_C^\dagger = \text{Tr}_A \left(U_A \otimes U_B \otimes U_C |\psi\rangle\langle\psi| (U_A \otimes U_B \otimes U_C)^\dagger)^a \right).$$

Since this holds for any power $a \in \mathbb{N}$, there exist a local unitary transformation $W_A$ on $\mathcal{H}_A$ such that

$$U_A \otimes U_{BC} |\psi\rangle\langle\psi| (U_A \otimes U_{BC})^\dagger = (W_A \otimes 1 \otimes 1) U_A \otimes U_B \otimes U_C |\psi\rangle\langle\psi| (U_A \otimes U_B \otimes U_C)^\dagger (W_A \otimes 1 \otimes 1)^\dagger$$

$$= W_A U_A \otimes U_B \otimes U_C |\psi\rangle\langle\psi| (W_A U_A \otimes U_B \otimes U_C)^\dagger.$$

Hence

$$|\psi^\prime\rangle = U_A \otimes U_{BC} |\psi\rangle = \tilde{U}_A \otimes U_B \otimes U_C |\psi\rangle,$$

where $\tilde{U}_A$ is equal $W_A U_A$ up to a phase factor. $\square$

Lemma 1 and Lemma 2 together give rise to the following proposition.

**Proposition 1** For pure states $|\psi\rangle$ and $|\psi^\prime\rangle$, $\rho = \text{Tr}_A (|\psi\rangle\langle\psi|)$ and $\rho^\prime = \text{Tr}_A (|\psi^\prime\rangle\langle\psi^\prime|)$, we have that $I^A_\alpha (|\psi^\prime\rangle) = I^A_\alpha (|\psi\rangle)$ for $\alpha = 1, \ldots, \min\{N_A, N_B \cdot N_C\}$ and $\rho^\prime = U_B \otimes U_C \rho U_B^\dagger \otimes U_C^\dagger$ for some $U_B \in U(\mathcal{H}_B)$, $U_C \in U(\mathcal{H}_C)$, if and only if $|\psi\rangle$ and $|\psi^\prime\rangle$ are equivalent under local unitary transformations.

**Remark.** A result corresponding to Lemma 1, Lemma 2, and Proposition 1 holds when tripartite is replaced by $n$–partite, for any $n \geq 3$, by splitting the system $A_1A_2\ldots A_n$ into, e.g., $A_1-A_2\ldots A_n$. 

3
New invariants

The next step is to find further invariants under local unitary transformations which give the same value for two states if and only if \( \rho' \) can be written as \( U_B \otimes U_C \rho U_B^\dagger \otimes U_C^\dagger \) for some unitary transformations \( U_B \in U(\mathcal{H}_B), U_C \in U(\mathcal{H}_C) \), the main obstacle being the fact that in general \( \rho \) is a bipartite mixed state and there is no general characterization of entanglement for that case.

The generalization of \( I_A^j(\langle \psi \rangle) \) to bipartite mixed states is \( \text{Tr}(\text{Tr}_j(\rho))^{\alpha} \), where \( j = B, C \). For a pure state \( |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C \) this means to consider the functions

\[
\text{Tr}(\text{Tr}_j(\text{Tr}_A |\psi\rangle \langle \psi|))^{\alpha}.
\]

Therefore we introduce the following set of new invariants

\[
I_{\alpha,\beta}^{j^k}(\langle \psi \rangle) = \text{Tr}(\text{Tr}_k(\text{Tr}_j |\psi\rangle \langle \psi|))^{\alpha\beta},
\]

where \( j, k \in \{A, B, C\}, j \neq k \), and \( \alpha, \beta \in \mathbb{N} \).

**Lemma 3** The functions \( I_{\alpha,\beta}^{j^k}(\langle \psi \rangle) \) defined in (1) are invariant under local unitary transformations \( U_A \otimes U_B \otimes U_C \).

**Proof.** As a model we consider \( I_{\alpha,\beta}^{A,B}(\langle \psi \rangle) \). The other cases can be treated in an analogous manner. We have

\[
\text{Tr}_A(\langle \psi \rangle \langle \psi|) = \sum_{j=1}^{N_A} \sum_{k=1}^{N_B} \sum_{l=1}^{N_C} \sum_{p=1}^{N_B} \sum_{q=1}^{N_C} a_{jklpq} |k\rangle \langle l| \langle p| \langle q|,
\]

where \( |k\rangle \) stands for \( |k\rangle_B \otimes |l\rangle_C \). Multiplying (2) \( \alpha \) times \( (\alpha \in \mathbb{N}) \) and calculating the partial trace on \( \mathcal{H}_B \) of the matrix obtained we get

\[
\text{Tr}_B(\text{Tr}_A |\psi\rangle \langle \psi|)^{\alpha} = \sum_{j_1=1}^{N_A} \sum_{p_1=1}^{N_B} \sum_{q_1=1}^{N_C} a_{j_1p_1q_1} a_{j_2p_2q_2} \cdots a_{j_\alpha p_\alpha q_\alpha} |j_1p_1q_1\rangle \langle j_\alpha p_\alpha q_\alpha|,
\]

and hence

\[
\text{Tr}(\text{Tr}_B(\text{Tr}_A |\psi\rangle \langle \psi|)^{\alpha\beta}) = \prod_{k=1}^{\beta} \left( \sum_{j_k=1}^{N_A} \sum_{p_k=1}^{N_B} \sum_{q_k=1}^{N_C} a_{j_k p_k q_k} a_{j_\alpha p_\alpha q_\alpha} a_{j_k p_k q_k \alpha} \right),
\]

where \( q_\alpha = \equiv q_\beta \). Instead of the one employed in the proof of Lemma 1, an alternative way to consider the factors \( a_{j kl} \) is by writing them in matrices \( (A^{(j)})_{kl} \); the index \( j \) sets the
considered matrix and $k, l$ describe the row and column of $A^{(j)}$, respectively. That is, we write $|\psi\rangle = \sum_{j=1}^{N_A} \sum_{k=1}^{N_B} \sum_{l=1}^{N_C} A_{kl}^{(j)} |jkl\rangle$. Using this notation, one obtains

$$\text{Tr}(\text{Tr}_B (\text{Tr}_A |\psi\rangle \langle \psi|) \alpha^\beta) = \sum_{j_1, \ldots, j_{n+1}=1}^{N_{A}} \prod_{k=1}^{\beta} \text{Tr}(A^{(j_{k_1})} A^{(j_{k_2})} \cdots A^{(j_{k_{\beta}})}) \cdot \text{Tr}(A^{(j_{k_{\beta+1}})} A^{(j_{k_{\beta+2}})} \cdots A^{(j_{k_{n+1}})}).$$

For a local unitary transformations $U \otimes V \otimes W$ we have

$$|\psi\rangle := U \otimes V \otimes W |\psi\rangle = \sum_{j_1, \ldots, j_{n+1}=1}^{N_A} \sum_{k=1}^{N_B} \sum_{l=1}^{N_C} A_{kl}^{(j)} |jkl\rangle$$

$$U \otimes V \otimes W |\psi\rangle = \sum_{j_1, \ldots, j_{n+1}=1}^{N_A} \sum_{k=1}^{N_B} \sum_{l=1}^{N_C} A_{kl}^{(j)} U_{m_j} V_{p_k} W_{q_l} |mpq\rangle = \sum_{j_1, \ldots, j_{n+1}=1}^{N_A} \sum_{k=1}^{N_B} \sum_{l=1}^{N_C} U_{m_j} (V A^{(m)} W^T)^{kl} |jkl\rangle,$$

i.e., $A_{kl}^{(j)} = \sum_{m=1}^{N_A} U_{m_j} (V A^{(m)} W^T)^{kl}$ and

$$\text{Tr}(A^{(p_{q_{r+1}})} A^{(p_{q_{r+2}})}) = \sum_{m_1, m_2=1}^{N_A} U_{m_1} U_{m_2} \text{Tr}(A^{(m_1)} A^{(m_2)}).$$

It follows that

$$\sum_{k=1}^{\beta} \prod_{k} \text{Tr}(A^{(j_{k_1})} A^{(j_{k_2})} \cdots A^{(j_{k_{\beta}})}) \cdot \text{Tr}(A^{(j_{k_{\beta+1}})} A^{(j_{k_{\beta+2}})} \cdots A^{(j_{k_{n+1}})}).$$

$$= \sum_{m_1, \ldots, m_{n+1}=1}^{N_A} \sum_{n_1, \ldots, n_{n+1}=1}^{N_A} \sum_{p_{\beta+1}, \ldots, p_{\beta+2}=1}^{N_B} \sum_{q_{\beta+1}, \ldots, q_{\beta+2}=1}^{N_C} U_{m_1} U_{n_1} U_{m_2} U_{n_2} U_{m_{\beta+1}} U_{n_{\beta+1}} \cdots U_{m_{n+1}} U_{n_{n+1}}$$

$$\cdot \text{Tr}(A^{(m_{\beta+1})} A^{(n_{\beta+1})}) \text{Tr}(A^{(m_{\beta+2})} A^{(n_{\beta+2})}) \cdots \text{Tr}(A^{(m_{n+1})} A^{(n_{n+1})})$$

$$\cdot \text{Tr}(U_{p_{\beta+1}, q_{\beta+1}} U_{p_{\beta+2}, q_{\beta+2}} U_{p_{\beta+3}, q_{\beta+3}} \cdots U_{p_{n+1}, q_{n+1}})$$

$$\cdot \text{Tr}(A^{(p_{\beta+1})} A^{(p_{\beta+2})} \cdots A^{(p_{n+1})}) A^{(q_{\beta+1})} \cdots A^{(q_{n+1})}).$$

The result follows, since $U$ is unitary and hence $\sum_{k} U_{j, k} = \delta_{j, \beta}$. □

**Remark.** The invariants $I_{\alpha, \beta}^{j,k}(|\psi\rangle)$ can easily be generalized to $n$-partite systems: the functions

$$I_{\alpha_1, \alpha_2, \ldots, \alpha_n}^{j_1, j_2, \ldots, j_n}(|\psi\rangle) = \text{Tr} \left( \text{Tr}_{j_1} \left( \text{Tr}_{j_2} \left( \cdots \left( \text{Tr}_{j_n} |\psi\rangle \langle \psi| \right)^{\alpha_1} \cdots \right)^{\alpha_n} \right)^{\alpha_{n+1}} \right),$$

$\alpha_i \in \mathbb{N}, \ i = 1, \ldots, n,$
are invariant under local unitary transformations $U_1 \otimes U_2 \otimes \cdots \otimes U_n$.

Unfortunately, the invariants (1) seem to be sufficient only in the case in which the $\lambda_j$ of the decomposition $\rho = \sum_{j=1}^{n} \lambda_j |\varphi_j \rangle \langle \varphi_j|$ where $n \leq N_B \cdot N_C$ and $\varphi_j \in \mathcal{H}_B \otimes \mathcal{H}_C$ for all $j$, are not degenerated, i.e., $\lambda_j \neq \lambda_k$ for $j \neq k$. Indeed, the following lemma holds.

**Lemma 4** Let $|\psi\rangle$ and $|\psi'\rangle$ be two tripartite pure states such that $I_{\alpha,\beta}^{j,k}(|\psi\rangle) = I_{\alpha,\beta}^{j,k}(|\psi'\rangle)$ for $j, k \in \{A, B, C\}$ and $j \neq k$, $\alpha = 1, \ldots, N_q \cdot N_r$, and $\beta = 1, \ldots, N_r$, where $q, r \in \{A, B, C\}$ and $r$ is different from $j$, $k$ and $q$. Then,

a) there exist $U_p \in \mathcal{U}(\mathcal{H}_p)$ and $U_{q,r} \in \mathcal{U}(\mathcal{H}_q \otimes \mathcal{H}_r)$, with $p, q, r$ different from each other, such that $|\psi'\rangle = U_p \otimes U_{q,r} |\psi\rangle$;

b) for any $|\varphi_m\rangle$ of the decomposition $\text{Tr}_p (|\psi\rangle \langle \psi|) = \sum_{m=1}^{n} \lambda_m^{(p)} |\varphi_m^{(p)}\rangle \langle \varphi_m^{(p)}|$ for which $\lambda_m^{(p)}$ is not degenerate we have

$$U_{q,r} |\varphi_m^{(p)}\rangle \langle \varphi_m^{(p)}| = u_{q}^{m} \otimes u_{r} |\varphi_m^{(p)}\rangle = u_{q} \otimes v_{r}^{m} |\varphi_m^{(p)}\rangle,$$

where $u_{q}^{m}, u_{q} \in \mathcal{U}(\mathcal{H}_q)$ and $u_{r}, v_{r}^{m} \in \mathcal{U}(\mathcal{H}_r)$.

**Proof.** Part a) was already proved in Lemma 1, since

$I_{\alpha}^{p,k}(|\psi\rangle) = I_{\alpha}^{p,k}(|\psi'\rangle) = I_{\alpha}^{p,k}(|\psi'\rangle)$. Further we know that $\text{Tr}_p (|\psi\rangle \langle \psi'|) = U_{q,r} \text{Tr}_p (|\psi\rangle \langle \psi'|) U_{q,r}^{\dagger}$. Since $I_{\alpha,\beta}^{j,k}(|\psi\rangle) = I_{\alpha,\beta}^{j,k}(|\psi'\rangle)$ for $\beta = 1, \ldots, N_r$, with $r$ different from $i$ and $k$, there exists a $u_{r} \in \mathcal{U}(\mathcal{H}_r)$ such that

$$\text{Tr}_k (\text{Tr}_i |\psi\rangle \langle \psi'|) = u_{r} \text{Tr}_k (\text{Tr}_i |\psi\rangle \langle \psi'|) = u_{r}^{\dagger}.$$ Therefore, since this result holds for all $\alpha = 1, \ldots, N_q \cdot N_r$, where $i, q, r$ are different from each other, and the $\lambda_m^{(p)}$ are not degenerated, for any $m$ there exists a $u_{q}^{m} \in \mathcal{U}(\mathcal{H}_q)$ such that

$$U_{q,r} |\varphi_m^{(p)}\rangle \langle \varphi_m^{(p)}| U_{q,r}^{\dagger} = \left( u_{q}^{m} \otimes 1 \right) (1 \otimes u_{r}) |\varphi_m^{(p)}\rangle \langle \varphi_m^{(p)}| (1 \otimes u_{r})^{\dagger} (u_{q}^{m} \otimes 1)^{\dagger}$$

$$= \left( u_{q}^{m} \otimes u_{r} \right) |\varphi_m^{(p)}\rangle \langle \varphi_m^{(p)}| (u_{q}^{m} \otimes u_{r})^{\dagger}.$$ The statement follows, as $|\langle \varphi_m^{(p)}| (u_{q}^{m} \otimes u_{r})^{\dagger} U_{q,r} |\varphi_m^{(p)}\rangle| = 1$. □

Remarks.

1. Lemma 4 b) is only sufficient if $\rho$ is a pure state.

2. For $n$-partite pure states the condition $I_{\alpha,\beta}^{j,k}(|\psi\rangle) = I_{\alpha,\beta}^{j,k}(|\psi'\rangle)$ for $j, k \in \{A_1, A_2, \ldots, A_n\}$ implies $|\psi\rangle = U_{p_1} \otimes U_{p_2, p_3, \ldots, p_n} |\psi\rangle$ for some $U_{p_1} \in \mathcal{U}(\mathcal{H}_{p_1})$, $U_{p_2, p_3, \ldots, p_n} \in \mathcal{U}(\mathcal{H}_{p_2} \otimes \cdots \otimes \mathcal{H}_{p_n})$ and

$$U_{p_2, \ldots, p_n} |\varphi_j^{(p_1)}\rangle = v_j^{p_2} \otimes u_{p_3, \ldots, p_n} |\varphi_j^{(p_1)}\rangle$$

for any $|\varphi_j^{(p_1)}\rangle$ of the decomposition $\text{Tr}_{p_1} (|\psi\rangle \langle \psi|) = \sum_{j=1}^{n_1} \lambda_j^{(p_1)} |\varphi_j^{(p_1)}\rangle \langle \varphi_j^{(p_1)}|$ such that $\lambda_j^{(p_1)}$ is not degenerated. Further

$$v_j^{p_3, \ldots, p_n} |\varphi_j^{(p_2)}\rangle = v_j^{p_3, \ldots, p_n} |\varphi_j^{(p_2)}\rangle = v_j^{p_3, \ldots, p_n} |\varphi_j^{(p_2)}\rangle$$

for $\text{Tr}_{p_2} (|\varphi_j^{(p_1)}\rangle \langle \varphi_j^{(p_1)}|) = \sum_{k=1}^{n_2} \lambda_k^{(p_2)} |\varphi_j^{(p_2)}\rangle \langle \varphi_j^{(p_2)}|$ and, if $\lambda_j^{(p_2)}$ and $\lambda_j^{(p_1)}$ are not degenerated, and so on. Note that only the invariants $I_{\alpha,\beta}^{j,k}$ were considered, and not $I_{\alpha_1,\alpha_2,\ldots,\alpha_n}^{j,k}$.
A special case for tripartite states

Complete sets of invariants for the case of bipartite mixed states are known only for some special cases. For example, in [21] a complete set was presented for the case in which the state \( \rho = \sum_{m=1}^{n} \lambda_m |\varphi_m\rangle \langle \varphi_m| \) is a generic mixed state. To define this set, we need further invariants:

\[
\Theta(\rho)_{jk} = \text{Tr} \left( \text{Tr}_B(|\varphi_j\rangle \langle \varphi_j|)^* \text{Tr}_B(|\varphi_k\rangle \langle \varphi_k|)^* \right), \quad \Omega(\rho)_{jk} = \text{Tr} \left( \text{Tr}_C(|\varphi_j\rangle \langle \varphi_j|) \text{Tr}_C(|\varphi_k\rangle \langle \varphi_k|) \right).
\]

Assume without loss of generality that \( N_B \leq N_C \). A bipartite mixed state is called generic if the \( (N_B^2 \times N_B^2) \)-matrices \( \Theta(\rho) \) and \( \Omega(\rho) \), where \( \Theta(\rho)_{jk} = \Omega(\rho)_{jk} = 0 \) for \( n < j, k \leq N_B^2 \), satisfy

\[
\det (\Theta(\rho)) \neq 0 \quad \text{and} \quad \det (\Omega(\rho)) \neq 0.
\]

If \( \rho \) is a generic mixed state and \( U \rho U^\dagger \), with \( U \) unitary, gives the same values as \( \rho \) for the invariants \( J_\alpha^\beta(\rho) = \text{Tr}(\text{Tr}_j(\rho^\beta)) \), where \( j \in \{B,C\} \), \( \Theta(\rho) \), \( \Omega(\rho) \), and

\[
Y(\rho)_{jkl} = \text{Tr} \left( \text{Tr}_B(|\varphi_j\rangle \langle \varphi_j|)^* \text{Tr}_B(|\varphi_k\rangle \langle \varphi_k|)^* \text{Tr}_B(|\varphi_l\rangle \langle \varphi_l|)^* \right),
\]
\[
X(\rho)_{jkl} = \text{Tr} \left( \text{Tr}_C(|\varphi_j\rangle \langle \varphi_j|) \text{Tr}_C(|\varphi_k\rangle \langle \varphi_k|) \text{Tr}_C(|\varphi_l\rangle \langle \varphi_l|) \right),
\]

where \( j, k, l = 1, \ldots, n \), then \( \rho \) and \( U \rho U^\dagger \) are equivalent under local unitary transformations [21]. That is, if \( \text{Tr}_A(|\psi\rangle \langle \psi|) \) is a generic mixed state and the above invariants give the same results for \( \text{Tr}_A(|\psi\rangle \langle \psi|) \) and \( \text{Tr}_A(|\psi\rangle \langle \psi'|) \), as well as \( I_{a}^\alpha(\psi) = I_{a}^\alpha(\psi') \) for \( \alpha = 1, \ldots, \min\{N_A, N_B^2\} \), \( |\psi\rangle \) and \( |\psi'\rangle \) are equivalent under local unitary transformations. The number of invariants one needs to calculate can be diminished if one considers (1) and takes into account Lemma 4. In fact we have

**Proposition 2** Let \( |\psi\rangle \) and \( |\psi'\rangle \) be two pure states of \( \mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C \) and assume that \( \rho = \text{Tr}_A(|\psi\rangle \langle \psi|) \) is a generic mixed state. \( |\psi\rangle \) is equivalent to \( |\psi'\rangle \) under local unitary transformations if and only if

\[
I_{a}^\alpha(\psi) = I_{a}^\alpha(\psi')
\]

for \( s \in \{B, C\}, \alpha = 1, \ldots, \min\{N_B^2, N_C^2\}, \beta = 1, \ldots, N_r \), where \( r \in \{B, C\} \) but is different from \( s \), and for \( \rho' = \text{Tr}_A(|\psi\rangle \langle \psi'|) \)

\[
\Theta(\rho)_{jk} = \Theta(\rho')_{jk}, \quad \Omega(\rho)_{jk} = \Omega(\rho')_{jk}, \quad Y(\rho)_{jkl} = Y(\rho')_{jkl}, \quad X(\rho)_{jkl} = X(\rho')_{jkl}
\]

for the \( j, k \) such that \( \lambda_j = \lambda_k \).

**Proof.** As remarked above, the invariants (4) are sufficient to establish whether two states for which the partial trace on \( \mathcal{H}_A \) is a generic mixed state are equivalent or not. It remains to prove that (4) is fulfilled when \( \lambda_j, \lambda_k, \) and \( \lambda_l \) are non-degenerate, if (3) holds. This follows from Lemma 4. Indeed, for example

\[
\text{Tr}_C(|\varphi_j\rangle \langle \varphi_j|) = \text{Tr}_C(U_{BC}|\varphi_j\rangle \langle \varphi_j|U_{BC}^\dagger) = \text{Tr}_C(u_B \otimes v_C^\dagger|\varphi_j\rangle \langle \varphi_j|)(u_B \otimes v_C^\dagger)^\dagger
\]
\[
= u_B \text{Tr}_C(1 \otimes v_C^\dagger|\varphi_j\rangle \langle \varphi_j|)(1 \otimes v_C^\dagger)^\dagger)u_B^\dagger = u_B \text{Tr}_C(|\varphi_j\rangle \langle \varphi_j|)u_B^\dagger,
\]

hence

\[
\Omega(\rho)_{jk} = \text{Tr} \left( \text{Tr}_C(|\varphi_j\rangle \langle \varphi_j|) \text{Tr}_C(|\varphi_k\rangle \langle \varphi_k|) \right) = \text{Tr}(u_B \text{Tr}_C(|\varphi_j\rangle \langle \varphi_j|)u_B^\dagger \text{Tr}_C(|\varphi_k\rangle \langle \varphi_k|)u_B^\dagger)
\]
\[
= \text{Tr} \left( \text{Tr}_C(|\varphi_j\rangle \langle \varphi_j|) \text{Tr}_C(|\varphi_k\rangle \langle \varphi_k|) \right) = \Omega(\rho)_{jk}.
\]
The same holds for \( \Theta(\rho) \), \( Y(\rho) \), and \( X(\rho) \). □

**Remark.** We know that the rank of \( \rho \) is smaller than \( \min\{N_A, N_B \cdot N_C\} \) (see, e.g., [31]). On the other hand, the assumption that \( \rho \) is a generic mixed state implies that \( \rho \) has full rank, i.e., \( N_B \cdot N_C \). Therefore, in order to fulfill the conditions of Proposition 2, we need \( N_A \geq N_B \cdot N_C \).

In this last section we have seen that a criterion for equivalence of a class of bipartite mixed states gives rise to a criterion of equivalence for a class of pure tripartite states. In [32], the complete invariants for another two classes of bipartite mixed states are given. For bipartite mixed states on \( \mathbb{C}^m \times \mathbb{C}^n \),

\[
\rho = \sum_{i=0}^{N} \mu_i \ket{\xi_i} \bra{\xi_i},
\]

where the rank of \( \rho \) is \( N + 1 \) (\( N \geq 1 \)), \( \mu_i \) are eigenvalues with corresponding eigenvectors \( \ket{\xi_i} = \sum_{ij} \xi_{ij} \ket{ij} \). Let \( A_l := (\xi_{ij}^{(l)}) \), \( \rho_l := A_l A_l^\dagger \), and \( \theta_l := A_l^\dagger A_l \), for \( l = 0, 1, \ldots, N \). If each eigenvalue of \( \rho_0 \) and \( \theta_0 \) has multiplicity one (i.e., is “multiplicity free”), then \( \rho \) belongs to the class of density matrices to which a complete set of invariants can be explicitly given. For rank two mixed states on \( \mathbb{C}^m \times \mathbb{C}^n \) such that each of the matrices \( \rho_0, \rho_1, \theta_0, \) and \( \theta_1 \) has at most two different eigenvalues, an operational criterion can be also found. From these criteria for bipartite mixed states, by using Lemma 4 we can similarly obtain criteria for some classes of pure tripartite states.

**Conclusion**

We have reduced the equivalence problem for \( n \)–partite pure states to the one for \((n-1)\)–partite mixed states and in the special case \( n = 3 \) we have constructed a set of invariants under local unitary transformations which is complete for the states with partial trace on \( \mathcal{H}_A \) which is a generic mixed state.

**Acknowledgments.** The second named author gratefully acknowledges the financial support by the Stefano Franscini Fund. The fourth author gratefully acknowledges the support provided by the China-Germany Cooperation Project 446 CHV 113/231, “Quantum information and related mathematical problems”.

**References**


Verzeichnis der erschienenen Preprints ab No. 180


181. Melikyan, Arik; Botkin, Nikolai; Turova, Varvara: Propagation of Disturbances in Inhomogeneous Anisotropic Media

182. Albeverio, Sergio; Bodnarchuk, Maksim; Koshmanenko, Volodymyr: Dynamics of Discrete Conflict Interactions between Non-Annihilating Opponents

183. Albeverio, Sergio; Daletskii, Alexei: $L^2$-Betti Numbers of Infinite Configuration Spaces

184. Albeverio, Sergio; Daletskii, Alexei: Recent Developments on Harmonic Forms and $L^2$-Betti Numbers of Infinite Configuration Spaces with Poisson Measures

185. Hildebrandt, Stefan; von der Mosel, Heiko: On Lichtenstein’s Theorem About Globally Conformal Mappings

186. Mandrekar, Vidyadhar; Rüdiger, Barbara: Existence and Uniqueness for Stochastic Integral Equations Driven by non Gaussian Noise on Separable Banach Spaces

187. Rüdiger, Barbara; Ziglio, Giacomo: Itô Formula for Stochastic Integrals w.r.t. Compensated Poisson Random Measures on Separable Banach Spaces


189. Strzelecki, Pawel; Mosel, Heiko von der: Global Curvature for Surfaces and Area Minimization Under a Thickness Constraint

190. Albeverio, Sergio; Cattaneo, Laura; Fei, Shao-Ming; Wang, Xiao-Hong: Equivalence of Tripartite Quantum States Under Local Unitary Transformations

191. Albeverio, Sergio; Fei, Shao-Ming, Goswami, Debashish: Local Invariants for a Class of Mixed States

192. Albeverio, Sergio; Schmitz, Marc; Steblovskaia, Victoria; Wallbaum, Kai: Poisson Processes in a Model with Interacting Assets

193. Albeverio, Sergio; Marinelli, Carlo: On the Reconstruction of the Drift of a Diffusion from Transition Probabilities which are Partially Observed in Space
194. Albeverio, Sergio; Kosyak, Alexandre: Group Action, Quasi-Invariant Measures and Quasi-
regular Representations of the Infinite-Dimensional Nilpotent Group

195. Albeverio, Sergio; Konstantinov, Alexei; Koshmanenko, Volodymyr: On Inverse Spectral
Theory for Singularly Perturbed Operators: Point Spectrum

196. Albeverio, Sergio; Motovilov, Alexander K.: Operator Integrals with Respect to a Spectral
Measure and Solutions to some Operator Equations

197. Giacomelli, Lorenzo; Grün, Günther: Lower Bounds on Waiting Time for Degenerate
Parabolic Equations and Systems

198. Albeverio, Sergio; Hryniv, Rostyslav; Mykytyuk, Yaroslav: Inverse Spectral Problems for
Dirac Operators with Summable Potentials; eingereicht bei: Russian J. Math. Physics

199. Albeverio, Sergio; Ayupov, Shavkat A.; Dadakhodjayev, Rashidhon A.: On Partially Ordered
Real Involutory Algebras; eingereicht bei: Acta Applicandae Mathematicae

200. Albeverio, Sergio; Ayupov, Shavkat A.; Omirov, Bakhrom A.: Cartan Subalgebras and
Criterion of Solvability of Finite Dimensional Leibniz Algebras; eingereicht bei: Journal
of Lie Theory

201. not published

202. Sturm, Karl-Theodor: Convex Functionals of Probability Measures and Nonlinear Diffusions

203. Sturm, Karl-Theodor: On the Geometry of Metric Measure Spaces

204. Müller, Jörn; Müller, Werner: Regularized Determinants of Laplace Type Operators, Analytic
Surgery and Relative Determinants

205. Mandrekar, Vidyadhar; Rüdiger, Barbara: Lévy Noises and Stochastic Integrals on Banach
Spaces

206. Albeverio, Sergio; Proskurin, Daniil; Turowska, Lyudmila: On *-Representations of the
λ-Deformation of a Wick Analogue of the CAR Algebra

207. Albeverio, Sergio; Fei, Shao-Ming; Song, Tong-Qiang: Multipartite Entangled State
Representation and its Squeezing Transformation

208. Albeverio, Sergio; Pratsiovytyi, Mykola; Torbin, Grygoriy: Topological and Fractal Properties
of Real Numbers which are not Normal; eingereicht bei: Bull. Sci. Math.

209. Albeverio, Sergio; Cattaneo, Laura; Fei, Shao-Ming; Wang, Xiao-Hong: Multipartite States
Under Local Unitary Transformations