Bases for spin systems and qudits from angular momentum theory

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Abstract: Spin bases of relevance for quantum systems with cyclic symmetry as well as for quantum information and quantum computation are constructed from the theory of angular momentum. This approach is connected to the use of generalized Pauli matrices (in dimension d) arising from a polar decomposition of the group SU_2. Numerous examples are given for d = 2, 3 and 4.

Keywords: Spin systems, qubits, qudits, generalized Pauli matrices, mutually unbiased bases, generalized Pauli group.

1. INTRODUCTION

Hilbert spaces of finite dimension d play an important role for the quantum mechanical description of dynamical systems and systems of qudits (qubits correspond to d = 2, qudits to d arbitrary). Generally speaking, bases for finite-dimensional subspaces of the representation space of the representations of SU_2 are important for the quantum mechanical description of dynamical systems (used in spectroscopy and quantum chemistry) and qudits (used in quantum information and quantum computation). Such bases can be constructed from tools developed for a study of supersymmetric quantum computation. Let us simply mention that the notation adopted here is the one used in quantum mechanics. Let us briefly mention that for the quantum mechanical description of dynamical systems, let us mention that the Weyl pairs and generalized Pauli group useful in quantum information theory, namely, mutually unbiased bases, play an important role for the quantum mechanical description of dynamical systems (used in spectroscopy and quantum chemistry) and qudits (used in quantum information and quantum computation) arising from a polar decomposition of the group SU_2. Numerous examples are given for d = 2, 3 and 4.

2. SPIN BASES

2.1 Angular momentum states

Let us consider a generalized angular momentum. We denote as j^2 and J_z its square and z-component, respectively. The common orthonormalized eigenvectors of the two commuting operators j^2 and J_z are written |j, m⟩. We know that

j^2|j, m⟩ = j(j + 1)|j, m⟩, \quad J_z|j, m⟩ = m|j, m⟩,

where m = j, j - 1, ..., -j and 2j ∈ N. For a fixed value of the quantum number j, we note E(2j + 1) ∼ C^{2j+1} the (2j + 1)-dimensional Hilbert space spanned by the basis

b_s = { |j, m⟩ : m = j, j - 1, ..., -j }.

The basis b_s is adapted to spherical symmetry (adapted to the group SO_3 if j ∈ N or SU_2 if 2j ∈ N).

In the applications to spectroscopy, the generalized angular momentum can be an orbital angular momentum, a spin angular momentum, a total (spin + orbital) angular momentum, a nucleus spin, etc. The vectors |j, m⟩ can thus have several realizations. For example, in the spectroscopy of a partly filled shell ion with configuration nd^N, we have state vectors of type |J, M⟩ ≡ |nℓ^N τ SL J M⟩ in the Russell-Saunders coupling (here \( j = J \) and \( m = M \)).

The vectors |j, m⟩ can also serve for quantum information and quantum computation. By introducing the notation

k = j - m, \quad |k⟩ = |j, m⟩, \quad d = 2j + 1,

we get the vectors |0⟩ (for m = j), |1⟩ (for m = j - 1), ..., |d - 1⟩ (for m = -j). The vectors |0⟩, |1⟩, ..., |d - 1⟩ are called qudits. Then, the basis b_s becomes...
where the complete set \( d \) and the notation shall play with the notation from the group \( \text{SU}_v \). In the rest of this paper, we shall use both the notation \( |k\rangle \) familiar in (i) quantum information and quantum computation and (ii) the description of cyclic systems (for which is referred to as the computational basis in quantum information and quantum computation and (ii) nuclear, atomic and molecular spectroscopy, and (iii) quantum chemistry. For \( d = 2 \), we shall play with the notation

\[
\alpha = \frac{1}{2} \left( \frac{1}{2} - \frac{1}{2} \right) = |0\rangle
\]

and

\[
\beta = \left| \frac{1}{2} \right| \left( \frac{1}{2} - \frac{1}{2} \right) = |1\rangle.
\]

2.2 A noncanonical basis for \( \text{SU}_2 \)

We now define the operator \( v_{0a} \) (a particular case of the unitary operator \( v_{0a} \) introduced in [21,22]) through

\[ v_{0a}|j, m\rangle = (1 - \delta_{m,j}) q^{(j-m)\alpha}|j, m + 1\rangle + \delta_{m,j}|j, -j\rangle
\]

or equivalently

\[ v_{0a}|k\rangle = q^{\alpha k}|k\rangle - 1,
\]

where \( a = 0, 1, \ldots, 2j = d - 1 \), \( q = \exp(2\pi i/d) \), and \( k - 1 \) should be understood modulo \( d \) (i.e., \( | - 1 \rangle = |d - 1\rangle \)). It is evident that the operators \( j^2 \) and \( v_{0a} \) commute so that the (complete) set \( \{j^2, v_{0a}\} \) constitutes an alternative to the set \( \{j^2, j_\pm\} \). The matrix \( V_{0a} \) of the linear operator \( v_{0a} \) on the basis \( b_k \equiv B_d \) reads

\[
V_{0a} = \begin{pmatrix}
0 & q^a & 0 & \cdots & 0 \\
0 & 0 & q^{2a} & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & q^{2ja} \\
1 & 0 & 0 & \cdots & 0
\end{pmatrix},
\]

where the \( d \) (\( = 2j + 1 \)) lines and \( d \) columns are labeled in the order \( |0\rangle = |j,j\rangle, |1\rangle = |j,j - 1\rangle, \ldots, |d - 1\rangle = |j,-j\rangle \).

By introducing the Hermitian operator \( h \) via

\[ h|j, m\rangle = \sqrt{(j + m)(j - m + 1)}|j, m\rangle
\]

or

\[ h|k\rangle = \sqrt{(d - 1 - k)(k + 1)}|k\rangle,
\]

it can be shown that the three operators

\[ j_+ = hv_{0a}, \quad j_- = v_{0a}^h h, \quad j_z = \frac{1}{2}(h^2 - v_{0a}^h h^2 v_{0a})
\]

satisfy the commutation relations

\[
[j_z, j_+ = +j_+, \quad [j_z, j_–] = -j_–, \quad [j_+, j_–] = 2j_z.
\]

Therefore, \( j_+, j_– \) and \( j_z \) span the Lie algebra \( \text{su}_2 \) and the operators \( v_{0a} \) and \( h \) realize a polar decomposition of \( \text{su}_2 \). The case \( d = 2 \) corresponds to qubits generated by \( |0\rangle \equiv | 00\rangle \) and \( |1\rangle \equiv | 11\rangle \) and \( |\alpha\rangle \equiv |a\alpha\rangle \). The matrix \( C \) of the linear operators \( j_\pm \) and \( j^2 \) introduced in [21,22] through

\[ v_{0a}|j, m\rangle = q^{(j-m)\alpha}|j, m + 1\rangle + \delta_{m,j}|j, -j\rangle
\]

is an orthonormal basis for \( E(d) \), which is an alternative to the basis \( B_d \).

3. APPLICATION TO QUANTUM INFORMATION

We are now in a position to discuss some results of interest for quantum information.

3.1 Weyl pairs

Besides the operator \( v_{0a} \), it is interesting to define the unitary operator \( z \) through

\[ z = (v_{00})^iv_{01}.
\]

This definition yields

\[ z|j, m\rangle = q^{i-m}|j, m\rangle \Rightarrow z|k\rangle = q^k|k\rangle.
\]

Therefore, we have the shift property

\[ z|\alpha\rangle = q^{-1}|\alpha a_1\rangle, \quad \alpha_1 = \alpha - 1.
\]

Furthermore, we can show that \( v_{0a} \) is connected to \( z \) and \( x = v_{00} \) by

\[ h|j, m\rangle = \sqrt{(j + m)(j - m + 1)}|j, m\rangle
\]
\[ v_{0a} = xz^a. \]

The two isospectral operators \( x \) (a shift operator when acting on \( |j, m\rangle \) and a phase operator when acting on \( |aa\rangle \)) and \( z \) (a phase operator when acting on \( |j, m\rangle \) and a shift operator when acting on \( |aa\rangle \)) are often called *shift operator* and *clock operator*, respectively, in quantum information and quantum computation. Note that for each \( x \) and \( z \), the *shift* or *clock* character depends on which state, \( |j, m\rangle \) or \( |aa\rangle \), the operator acts. The operators \( v_{0a} \) and \( z \) satisfy
\[
\alpha x + \beta z = (\alpha x + \beta z) = 0.
\]

In other words, the unitary operators \( v_{0a} \) and \( z \) are cyclic (up to a phase factor for \( v_{0a} \) with \( a \neq 0 \)) and do not commute. The pair \( (x, z) \) corresponds to \( x = 0 \) is a Weyl pair in the sense that \( x^d = z^{-d} = 1 \) and \( xz = qzx \). Such a pair can be used as an integrity basis for constructing the Lie algebra of the unitary group \( U_d \) [24].

In the basis \( B_d \), the \( d \)-dimensional matrices \( X \) and \( Z \) of the linear operators \( x \) and \( z \) are given by
\[
X = \begin{pmatrix}
0 & 1 & 0 & \ldots & 0 \\
0 & 0 & 1 & \ldots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & 0 & \ldots & 1 \\
1 & 0 & 0 & \ldots & 0
\end{pmatrix}
\]
and
\[
Z = \begin{pmatrix}
1 & 0 & 0 & \ldots & 0 \\
0 & q & 0 & \ldots & 0 \\
0 & 0 & q^2 & \ldots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & 0 & \ldots & q^{d-1}
\end{pmatrix}.
\]

For \( d = 2 \leftrightarrow j = 1/2 \) (\( \Rightarrow q = -1 \)), the matrices \( V_{00}, V_{01}, \) and \( Z \) are connected to the Pauli matrices \( \sigma_x, \sigma_y, \) and \( \sigma_z \) via
\[
V_{00} = X = \sigma_x, \quad V_{01} = XZ = -i\sigma_y, \quad Z = \sigma_z.
\]

For \( d \) arbitrary, the pair \( (X = V_{00}, Z = V_{01}V_{01}) \) are basic ingredients for generating generalized Pauli matrices and a generalized Pauli group \( \hat{H}_d \) of interest in quantum computation for quantum correcting codes [24,25].

### 3.2 Mutually unbiased bases

We now give two applications to MUBs.

First, in the general case where \( d \) is arbitrary, we can check that
\[
|\langle k | a \rangle | = \frac{1}{\sqrt{d}}, \quad k, a, \alpha \in \mathbb{Z}_d
\]
and
\[
|\langle 0a | 1 \rangle | = \frac{1}{\sqrt{d}}, \quad \alpha, \beta \in \mathbb{Z}_d,
\]
where we use \( \langle \ | \rangle \) to denote the inner product in \( E(d) \). In the terminology of quantum information, the latter two equations mean that the bases \( B_d, B_00, \) and \( B_01 \) are three MUBs. This result is in agreement with the one according to which there exist at least three MUBs in arbitrary dimension, see for instance [17].

Second, in the special case where \( d = p \) is a prime number, the latter equation can be extended to
\[
|\langle aa | b \beta \rangle | = \delta_{a, b} \delta_{a, b} + \frac{1}{\sqrt{p}} (1 - \delta_{a, b}), \quad a, b, \alpha, \beta \in \mathbb{Z}_d.
\]

The proof follows from the use of generalized quadratic Gauss sums [21]. Hence, the bases \( B_00, B_01, \ldots, B_{q,p-1} \), and \( B_p \) constitute a (maximal) set of \( d + 1 \) MUBs. This result is a particular case of the one according to which there exist a maximal set of \( d + 1 \) MUBs when \( d \) is the power of a prime number [8–17].

We continue with some typical examples of interest for quantum information and quantum computation.

### 4. EXAMPLES

#### 4.1 The case \( d = 2 \)

In this case, relevant for a spin \( j = 1/2 \) or for a qubit, we have \( q = -1 \) and \( a, \alpha \in \mathbb{Z}_2 \). The matrices of the operators \( v_{0a} \) are
\[
V_{00} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \sigma_x, \quad V_{01} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = -i\sigma_y.
\]

The \( d + 1 = 3 \) MUBs \( B_2, B_{00}, \) and \( B_{01} \) are the following.

The \( B_2 \) basis:
\[
|0\rangle, \quad |1\rangle.
\]

The \( B_{00} \) basis:
\[
|00\rangle = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle), \quad |01\rangle = \frac{1}{\sqrt{2}} (-|0\rangle + |1\rangle).
\]

The \( B_{01} \) basis:
\[
|10\rangle = \frac{1}{\sqrt{2}} (i|0\rangle + |1\rangle), \quad |11\rangle = \frac{1}{\sqrt{2}} (-i|0\rangle + |1\rangle).
\]

or, by using the spinorbitals \( \alpha \) and \( \beta \), we get

The \( B_2 \) basis:
\[
\alpha, \quad \beta.
\]

The \( B_{00} \) basis:
\[
|00\rangle = \frac{1}{\sqrt{2}} (\alpha + \beta), \quad |01\rangle = -\frac{1}{\sqrt{2}} (\alpha - \beta).
\]

The \( B_{01} \) basis:
\[
|10\rangle = \frac{1}{\sqrt{2}} (\alpha - i\beta), \quad |11\rangle = -\frac{1}{\sqrt{2}} (\alpha + i\beta).
\]

In terms of eigenvectors of the matrices \( V_{0a} \), we must replace the state vectors \( |aa\rangle \) by column vectors. This leads to
The $B_2$ basis:

$$\alpha \rightarrow \left( \begin{array}{c} 1 \\ 0 \end{array} \right), \quad \beta \rightarrow \left( \begin{array}{c} 0 \\ 1 \end{array} \right).$$

The $B_{00}$ basis:

$$|00\rangle \rightarrow \frac{1}{\sqrt{2}} \left( \begin{array}{c} 1 \\ 1 \end{array} \right), \quad |01\rangle \rightarrow -\frac{1}{\sqrt{2}} \left( \begin{array}{c} 1 \\ -1 \end{array} \right).$$

The $B_{01}$ basis:

$$|10\rangle \rightarrow \frac{1}{\sqrt{2}} \left( \begin{array}{c} 1 \\ -i \end{array} \right), \quad |11\rangle \rightarrow -\frac{1}{\sqrt{2}} \left( \begin{array}{c} 1 \\ i \end{array} \right).$$

4.2 The case $d = 3$

This case corresponds to a spin $j = 1$ or to a qutrit. Here, we have $q = \exp(2\pi i/3)$ and $a, \alpha \in \mathbb{Z}_3$. The matrices of the operators $v_{00}, v_{01}$, and $v_{02}$ are the following.

The $B_{3}$ basis:

$$|0\rangle, \quad |1\rangle, \quad |2\rangle.$$

The $B_{00}$ basis:

$$|00\rangle = \frac{1}{\sqrt{3}} (|0\rangle + |1\rangle + |2\rangle)$$

$$|01\rangle = \frac{1}{\sqrt{3}} (q^2|0\rangle + q|1\rangle + |2\rangle)$$

$$|02\rangle = \frac{1}{\sqrt{3}} (q|0\rangle + q^2|1\rangle + |2\rangle).$$

The $B_{01}$ basis:

$$|10\rangle = \frac{1}{\sqrt{3}} (q|0\rangle + q|1\rangle + |2\rangle)$$

$$|11\rangle = \frac{1}{\sqrt{3}} (|0\rangle + q^2|1\rangle + |2\rangle)$$

$$|12\rangle = \frac{1}{\sqrt{3}} (q^2|0\rangle + |1\rangle + |2\rangle).$$

The $B_{02}$ basis:

$$|20\rangle = \frac{1}{\sqrt{3}} (q^2|0\rangle + q^2|1\rangle + |2\rangle)$$

$$|21\rangle = \frac{1}{\sqrt{3}} (q|0\rangle + |1\rangle + |2\rangle)$$

$$|22\rangle = \frac{1}{\sqrt{3}} (|0\rangle + q|1\rangle + |2\rangle).$$

This can be transcribed in terms of column vectors as follows.

The $B_{3}$ basis:

$$|0\rangle \rightarrow \left( \begin{array}{c} 1 \\ 0 \end{array} \right), \quad |1\rangle \rightarrow \left( \begin{array}{c} 0 \\ 1 \end{array} \right), \quad |2\rangle \rightarrow \left( \begin{array}{c} 0 \\ 0 \end{array} \right).$$

The $B_{00}$ basis:

$$|00\rangle \rightarrow \frac{1}{\sqrt{3}} \left( \begin{array}{c} 1 \\ 1 \end{array} \right), \quad |01\rangle \rightarrow \frac{1}{\sqrt{3}} \left( \begin{array}{c} q^2 \\ q \end{array} \right), \quad |02\rangle \rightarrow \frac{1}{\sqrt{3}} \left( \begin{array}{c} q \\ q \end{array} \right).$$

The $B_{01}$ basis:

$$|10\rangle \rightarrow \frac{1}{\sqrt{3}} \left( \begin{array}{c} q \\ q \end{array} \right), \quad |11\rangle \rightarrow \frac{1}{\sqrt{3}} \left( \begin{array}{c} 1 \\ 1 \end{array} \right), \quad |12\rangle \rightarrow \frac{1}{\sqrt{3}} \left( \begin{array}{c} 1 \\ q \end{array} \right).$$

The $B_{02}$ basis:

$$|20\rangle \rightarrow \frac{1}{\sqrt{3}} \left( \begin{array}{c} q^2 \\ q \end{array} \right), \quad |21\rangle \rightarrow \frac{1}{\sqrt{3}} \left( \begin{array}{c} q \\ 1 \end{array} \right), \quad |22\rangle \rightarrow \frac{1}{\sqrt{3}} \left( \begin{array}{c} 1 \\ q \end{array} \right).$$

4.3 The case $d = 4$

This case corresponds to a spin $j = 3/2$. Here, we have $q = i$ and $a, \alpha \in \mathbb{Z}_4$. The five bases $B_1, B_0, B_0, B_0, B_0$ and $B_0$ do not constitute a system of MUBs ($d = 4$ is not a prime number). Nevertheless, it is possible to find $d + 1 = 5$ MUBs because $d = 2^k$ is the power of a prime number. This can be achieved by replacing the space $E(4)$ spanned by $\{|3/2, m\} : m = 3/2, 1/2, -1/2, -3/2\}$ by the tensor product space $E(2) \otimes E(2)$ spanned by the canonical (or computational) basis

$$\{|\alpha \otimes \alpha, \alpha \otimes \beta, \beta \otimes \alpha, \beta \otimes \beta\}.$$

The space $E(2) \otimes E(2)$ is associated with the coupling of two spin angular momenta $j_1 = 1/2$ and $j_2 = 1/2$ or two qubits (in the vector $u \otimes v$, $u$ and $v$ correspond to $j_1$ and $j_2$, respectively). An alternative basis for $E(2) \otimes E(2)$ is the $SU_2$ adapted basis

$$\{|\alpha \otimes \alpha, \frac{1}{2}(\alpha \otimes \beta + \beta \otimes \alpha), \beta \otimes \beta, \frac{1}{2}(\alpha \otimes \beta - \beta \otimes \alpha)\},$$

the vectors of which are well-known in the treatment of spin systems. Such a basis corresponds to the decomposition

$$(1/2) \otimes (1/2) = (1) \otimes (0)$$

in terms of irreducible representation classes of $SU_2$. In the $SU_2$ adapted basis, the first three vectors are symmetric under the interchange $1 \leftrightarrow 2$ and describe a total angular momentum $J = 1$ while the last one is antisymmetric and corresponds to $J = 0$. It should be observed that the $SU_2$ adapted basis illustrates a connection between the special unitary group $SU_2$ and the permutation group $S_2$ (a particular case of the Schur-Weyl duality theorem between
irreducible representation classes of the linear group $GL_d$ and the symmetric group $S_n$).

In addition to the computational or canonical basis and the SU$_2$ adapted basis, it is possible to find other bases of $\mathcal{E}(2) \otimes \mathcal{E}(2)$ which are mutually unbiased. As a matter of fact, $d = 4$ MUBs, besides the computational basis \{\(\langle \alpha \otimes \alpha, \beta \otimes \beta \rangle\), correspond to the eigenvectors of the operators \(w_{ab} = v_{0a} \otimes v_{0b}\) (the vectors \(\langle \alpha \rangle\) and \(\langle \beta \rangle\) refer to the two spaces \(\mathcal{E}(2)\)). As a result, we have the \(d + 1 = 5\) following MUBs where \(\lambda = (1 - i)/2\) and \(\mu = (1 + i)/2\).

**The canonical basis:**

\[
\begin{align*}
\alpha \otimes \alpha, & \quad \alpha \otimes \beta, \quad \beta \otimes \alpha, \quad \beta \otimes \beta
\end{align*}
\]

or in column vectors

\[
\begin{pmatrix}
1 \\
0 \\
0 \\
0 \\
0
\end{pmatrix}, \quad \begin{pmatrix}
0 \\
1 \\
0 \\
0 \\
0
\end{pmatrix}, \quad \begin{pmatrix}
0 \\
0 \\
1 \\
0 \\
0
\end{pmatrix}, \quad \begin{pmatrix}
0 \\
0 \\
0 \\
1 \\
0
\end{pmatrix}.
\]

**The \(w_{00}\) basis:**

\[
\begin{align*}
|0000\rangle &= \frac{1}{2} (\alpha \otimes \alpha + \alpha \otimes \beta + \beta \otimes \alpha + \beta \otimes \beta) \\
|0001\rangle &= \frac{1}{2} (\alpha \otimes \alpha - \alpha \otimes \beta + \beta \otimes \alpha - \beta \otimes \beta) \\
|0010\rangle &= \frac{1}{2} (\alpha \otimes \alpha + \alpha \otimes \beta - \beta \otimes \alpha - \beta \otimes \beta) \\
|0011\rangle &= \frac{1}{2} (\alpha \otimes \alpha - \alpha \otimes \beta - \beta \otimes \alpha + \beta \otimes \beta)
\end{align*}
\]

or in column vectors

\[
\begin{pmatrix}
1 \\
1 \\
1 \\
1 \\
1
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
-1 \\
-1 \\
-1 \\
-1
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
-1 \\
-1 \\
1 \\
1
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
1 \\
1 \\
-1 \\
-1
\end{pmatrix}.
\]

**The \(w_{11}\) basis:**

\[
\begin{align*}
|1100\rangle &= \frac{1}{2} (\alpha \otimes \alpha + i \alpha \otimes \beta + i \beta \otimes \alpha - \beta \otimes \beta) \\
|1101\rangle &= \frac{1}{2} (\alpha \otimes \alpha - i \alpha \otimes \beta + i \beta \otimes \alpha + \beta \otimes \beta) \\
|1110\rangle &= \frac{1}{2} (\alpha \otimes \alpha + i \alpha \otimes \beta - i \beta \otimes \alpha + \beta \otimes \beta) \\
|1111\rangle &= \frac{1}{2} (\alpha \otimes \alpha - i \alpha \otimes \beta - i \beta \otimes \alpha - \beta \otimes \beta)
\end{align*}
\]

or in column vectors

\[
\begin{pmatrix}
1 \\
i \\
i \\
-1
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
-1 \\
i \\
-1
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
i \\
-1 \\
1
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
i \\
i \\
1
\end{pmatrix}.
\]

**The \(w_{01}\) basis:**

\[
\begin{align*}
|0100\rangle + \mu |0111\rangle &= \frac{1}{2} (\alpha \otimes \alpha + \alpha \otimes \beta - i \beta \otimes \alpha + i \beta \otimes \beta) \\
\mu |0100\rangle + |0111\rangle &= \frac{1}{2} (\alpha \otimes \alpha - \alpha \otimes \beta + i \beta \otimes \alpha + i \beta \otimes \beta) \\
\lambda |0101\rangle + \mu |0110\rangle &= \frac{1}{2} (\alpha \otimes \alpha - \alpha \otimes \beta - i \beta \otimes \alpha - i \beta \otimes \beta) \\
\mu |0101\rangle + \lambda |0110\rangle &= \frac{1}{2} (\alpha \otimes \alpha + \alpha \otimes \beta + i \beta \otimes \alpha - i \beta \otimes \beta)
\end{align*}
\]

or in column vectors

\[
\begin{pmatrix}
1 \\
-1 \\
i \\
i
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
i \\
-1 \\
1
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
1 \\
i \\
i
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
i \\
i \\
1
\end{pmatrix}.
\]

The \(w_{10}\) basis:

\[
\begin{align*}
\lambda |1000\rangle + \mu |1011\rangle &= \frac{1}{2} (\alpha \otimes \alpha - i \alpha \otimes \beta + \beta \otimes \alpha + i \beta \otimes \beta) \\
\mu |1000\rangle + \lambda |1011\rangle &= \frac{1}{2} (\alpha \otimes \alpha + i \alpha \otimes \beta - \beta \otimes \alpha + i \beta \otimes \beta) \\
\lambda |1001\rangle + \mu |1010\rangle &= \frac{1}{2} (\alpha \otimes \alpha + i \alpha \otimes \beta + \beta \otimes \alpha - i \beta \otimes \beta) \\
\mu |1001\rangle + \lambda |1010\rangle &= \frac{1}{2} (\alpha \otimes \alpha - i \alpha \otimes \beta - \beta \otimes \alpha - i \beta \otimes \beta)
\end{align*}
\]

or in column vectors

\[
\begin{pmatrix}
1 \\
-1 \\
i \\
i
\end{pmatrix}, \quad \begin{pmatrix}
1 \\
i \\
1 \\
1
\end{pmatrix}, \quad \begin{pmatrix}
i \\
1 \\
-1 \\
1
\end{pmatrix}, \quad \begin{pmatrix}
i \\
i \\
i \\
1
\end{pmatrix}.
\]

It is to be noted that the vectors of the \(w_{00}\) and \(w_{11}\) bases are not intricated (i.e., each vector is the direct product of two vectors) while the vectors of the \(w_{01}\) and \(w_{10}\) bases are intricated (i.e., each vector is not the direct product of two vectors).

To be more precise, the degree of intrication of the state vectors for the bases \(w_{00}, w_{11}, w_{01},\) and \(w_{10}\) can be determined in the following way. In arbitrary dimension \(d,\) let

\[
|\Phi\rangle = \sum_{k=0}^{d-1} \sum_{l=0}^{d-1} a_{kl} |k\rangle \otimes |l\rangle
\]

be a double qubit state vector. Then, it can be shown that the determinant of the \(d \times d\) matrix \(A = (a_{kl})\) satisfies

\[
0 \leq |\det A| \leq \frac{1}{\sqrt{d^d}}
\]

as proved in the Albouy thesis [26]. The case \(\det A = 0\) corresponds to the absence of global intrication while the case

\[
|\det A| = \frac{1}{\sqrt{d^d}}
\]

corresponds to a maximal intrication. As an illustration, we obtain that all the state vectors for \(w_{00}\) and \(w_{11}\) are not intricated and that all the state vectors for \(w_{01}\) and \(w_{10}\) are maximally intricated.
5. CONCLUSION

We presented some results concerning bases of interest for spin systems and quantum information. It should be noted that the bases derived in the present work are adapted to cyclic symmetry and can be used for describing finite or infinite cyclic systems. As an extension of this paper and of its companion paper [24], it would be interesting to examine when $d$ is a composite number how the Weyl pair $(X, Z)$ and the corresponding generalized Pauli group $P_d$ are connected to the Weyl pairs and the corresponding generalized Pauli group for each of the composite dimension.

We close with a comment on the group $P_d$. Such a group can be generated from the Weyl pair $(X, Z)$. Indeed, the group $P_d$ is a finite group of order $d^3$ with elements $q^a X^b Z^c$ (where $a, b, c \in \mathbb{Z}_d$) and matrix multiplication for group law. It is a subgroup of the unitary group $U_d$. The normaliser of $P_d$ in $U_d$ is a Clifford-type group in $d$ dimensions noted $C_d$. More precisely, $C_d$ is the set $\{ U \in U_d | U P_d U^\dagger = P_d \}$ endowed with matrix multiplication. The Pauli group $P_d$ as well as any other invariant subgroup of $C_d$ can be used for stabilizing errors in quantum computing. These concepts are very important in the case of n-qubit systems (corresponding to $d = 2^n$). These matters, in connection with the decomposition of $P_{2^n}$ in terms of $P_2$, are the object of a future work.

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REFERENCES


