Positive operator valued measures covariant with respect to an Abelian group

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Given a unitary representation $U$ of an Abelian group $G$ and a subgroup $H$, we characterize the positive operator valued measures based on the quotient group $G/H$ and covariant with respect to $U$. © 2004 American Institute of Physics. DOI: 10.1063/1.1631081

I. INTRODUCTION

Usually, the observables in quantum mechanics are represented by self-adjoint operators acting in the Hilbert space of states, or, equivalently, by projection valued operator measures. However, in quantum theory of measurement and in its applications (such as quantum optics or theory of measurement in phase-space) one needs to consider a more general setting in which projectivity is dropped and generalized observables are described in terms of positive operator valued measures (for a review see, for example, Refs. 1, 2, 6, 10, 13, and 14). Among these measures, the physically significant ones satisfy certain properties of covariance with respect to a symmetry group of the theory.

More precisely, consider a topological group $G$ and a closed subgroup $H$. Given a unitary representation $U$ of $G$, it is of interest both in quantum mechanics and in wavelet analysis to describe the positive operator valued measures $Q$ defined on the quotient space $G/H$ and covariant with respect to $U$.

In his seminal papers, 11,12 Holevo classifies the covariant positive operator valued measures if $G$ is of type I and $H = \{e\}$, and if $G$ is compact and $H$ is arbitrary.

In this article we extend the above result to the case $G$ Abelian and $H$ arbitrary. Moreover, we give a more feasible description of covariant positive operator valued measures in terms of a family $W_x : E_x \to E$ of isometries, where the index $x$ runs over the dual group of $G$, dim $E_x$ equals the multiplicity of the character $x$ in $U$ and $E$ is a fixed (infinite dimensional) Hilbert space. As a byproduct, we define a unitary operator $\Sigma$ that diagonalizes the representation of $G$ unitarily induced by a representation of $H$ with uniform multiplicity.

As an application of our characterization, in the final section we give three examples of physical interest:

(1) the regular representation of the real line, where the positive operator valued measures describe the position observables in one dimension;

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(2) the number-representation of the torus, where the positive operator valued measures describe the phase observables, and

(3) the tensor product of two number-representations of the torus, where the positive operator valued measures describe the phase difference observables.

II. NOTATIONS

In this article, by Hilbert space we mean a separable complex Hilbert space with scalar product \( \langle \cdot, \cdot \rangle \) linear in the first argument, by group we mean a locally compact second countable Abelian group and by representation a continuous unitary representation of a group acting on a Hilbert space. If \( X \) is a locally compact second countable topological space, we denote by \( B(X) \) the Borel \( \sigma \)-algebra of \( X \) and by \( C_c(X) \) the space of continuous complex functions on \( X \) with compact support. By measure we mean a positive measure defined on \( B(X) \) and finite on compact sets.

In the sequel we shall use rather freely basic results of harmonic analysis on Abelian groups, as exposed, for example, in Refs. 7 and 8.

We fix a group \( G \) and a closed subgroup \( H \). We denote by \( \hat{G} \) and \( \hat{H} \) the corresponding dual groups and by \( \langle x, g \rangle \) the canonical pairing.

We denote by

\[ q: G \rightarrow G/H, \quad q(g) = \dot{g} \]

the canonical projection onto the quotient group \( G/H \). If \( a \in G \) and \( \dot{g} \in G/H \), we let \( a[\dot{g}] = q(\dot{g}) = \dot{a} \dot{g} \) be the natural action of \( a \) on the point \( \dot{g} \).

Let \( H^\perp \) be the annihilator of \( H \) in \( \hat{G} \), that is,

\[ H^\perp = \{ y \in \hat{G} | \langle y, h \rangle = 1 \ \forall h \in H \}. \]

The group \( H^\perp \) is a closed subgroup of \( \hat{G} \) and \( \hat{G}/H \) can be identified (and we will do that) with \( H^\perp \) by means of

\[ \langle y, \dot{g} \rangle = \langle y, g \rangle \quad \forall y \in H^\perp, \forall \dot{g} \in G/H. \]

Since \( H^\perp \) is closed, we can consider the quotient group \( \hat{G}/H^\perp \). We denote by

\[ \pi: \hat{G} \rightarrow \hat{G}/H^\perp, \quad \pi(x) = \dot{x} \]

the canonical projection. The group \( \hat{H} \) can be identified (and we will do that) with the quotient group \( \hat{G}/H^\perp \) by means of

\[ \langle \dot{x}, h \rangle = \langle x, h \rangle \quad \forall \dot{x} \in \hat{G}/H^\perp, \forall h \in H. \]

Let \( \mu_G \), \( \mu_H \) and \( \mu_{G/H} \) be fixed Haar measures on \( G \), \( H \) and \( G/H \), respectively.

We denote by \( \mu_{H^\perp} \) the Haar measure on \( H^\perp \) such that the Fourier–Plancherel cotransform \( \hat{F}_{G/H} \) is unitary from \( L^2(G/H, \mu_{G/H}) \) onto \( L^2(H^\perp, \mu_{H^\perp}) \), where \( \hat{F}_{G/H} \) is given by

\[ (\hat{F}_{G/H} f)(y) = \int_{G/H} \langle y, \dot{g} \rangle f(\dot{g}) d\mu_{G/H}(\dot{g}), \quad y \in H^\perp, \]

for all \( f \in (L^1 \cap L^2)(G/H, \mu_{G/H}) \).

Given \( \varphi \in C_c(\hat{G}) \), let
\[ \tilde{\varphi}(\hat{x}) := \int_{H^+} \varphi(xy) d\mu_{H^+}(y) \quad \forall \hat{x} \in \hat{G}/H^+. \]

It is well known that \( \tilde{\varphi} \) is in \( C_c(\hat{G}/H^+) \) and that \( \tilde{\varphi} \geq 0 \) if \( \varphi \geq 0 \). Given a measure \( \nu \) on \( \hat{G}/H^+ \), the map

\[ C_c(\hat{G}) \ni \varphi \mapsto \int_{\hat{G}/H^+} \tilde{\varphi}(\hat{x}) d\nu(\hat{x}) \in \mathbb{C} \tag{1} \]

is linear and positive. Hence, by Riesz–Markov theorem, there is a unique measure \( \tilde{\nu} \) on \( \hat{G} \) such that

\[ \int_{\hat{G}} \phi(\hat{x}) d\tilde{\nu}(\hat{x}) = \int_{\hat{G}/H^+} \tilde{\nu}(\hat{x}) \int_{H^+} \phi(xy) d\mu_{H^+}(y) \]

for all \( \phi \in L^1(\hat{G}, \tilde{\nu}) \). One can check that the correspondence \( \nu \mapsto \tilde{\nu} \) preserves equivalence and orthogonality of measures.

Given a finite measure \( \mu \) on \( \hat{G} \), we denote by \( \mu^\pi \) the image measure of \( \mu \) with respect to \( \pi \), i.e., the measure on \( \hat{G}/H^+ \) given by

\[ \mu^\pi(A) = \mu(\pi^{-1}(A)) \quad \forall A \in \mathcal{B}(\hat{G}/H^+). \]

We fix a representation \( U \) of \( G \) acting on a Hilbert space \( \mathcal{H} \). Let \( Q \) be a positive operator valued measure (POVM) defined on \( G/H \) and acting on \( \mathcal{H} \). If \( Q \) satisfies the following properties,

1. \( Q(G/H) = I \),
2. \( U(g)Q(X)U(g)^{-1} = Q([g][X]) \quad \forall g \in G, \)

it is called covariant and \((U, Q)\) is said to be a covariance system. In particular, if \( Q \) is a projective measure, \((U, Q)\) is called an imprimitivity system.

For \( \omega \in C_c(G/H) \), we define the operator

\[ M(\omega) := \int_{G/H} \omega(\hat{g}) dQ(\hat{g}). \]

The map \( \omega \mapsto M(\omega) \) defines uniquely the POVM \( Q \). In the following we use \( M \) instead of \( Q \).

Finally, given a representation \( \sigma \) of \( H \), we denote by \((\text{ind}_{H}^{G}(\sigma), M_{\sigma})\) the imprimitivity system induced by \( \sigma \) from \( H \) to \( G \).

The aim of this article is to describe all the positive operator valued measures covariant with respect to \( U \). The generalized imprimitivity theorem (see, for example, Refs. 4 and 5) states the following.

**Theorem 1:** A POVM \( M \) based on \( G/H \) and acting on \( \mathcal{H} \) is covariant with respect to \( U \) if and only if there exists a representation \( \sigma \) of \( H \) and an isometry \( W \) intertwining \( U \) with \( \text{ind}_{H}^{G}(\sigma) \) such that

\[ M(\omega) = W^* M_{\omega}(\omega) W \]

for all \( \omega \in C_c(G/H) \).

If \( \sigma' \) is another representation of \( H \) such that \( \sigma \) is contained (as subrepresentation) in \( \sigma' \), then \((\text{ind}_{H}^{G}(\sigma), M_{\sigma})\) is contained (as an imprimitivity system) in \((\text{ind}_{H}^{G}(\sigma'), M'_{\sigma'})\). Hence, we can always assume that \( \sigma \) in the previous theorem has infinite multiplicity.
Moreover, there exist a measure $\nu$ on $\hat{G}/H^\perp$ and an infinite dimensional Hilbert space $E$ such that, up to a unitary equivalence, $\sigma$ acts diagonally on $L^2(\hat{G}/H^\perp, \nu; E)$. The first step of our construction is to diagonalize the representation $\text{ind}_{\hat{G}}^G(\sigma)$.

### III. DIAGONALIZATION OF $\text{ind}_{\hat{G}}^G(\sigma)$

In this section, given a representation of $H$ with uniform multiplicity, we diagonalize the corresponding induced representation.

Let $\nu$ be a measure on $\hat{G}/H^\perp$ and $E$ be a Hilbert space. Let $\sigma^\nu$ be the diagonal representation of $H$ acting on the space $L^2(\hat{G}/H^\perp, \nu; E)$, that is,

$$(\sigma^\nu(h)\xi)(\hat{x}) = (\hat{x}, h)\xi(\hat{x}), \quad \hat{x} \in \hat{G}/H^\perp,$$

where $h \in H$.

We denote by $\mathcal{H}^\nu$ the space of functions $f: \hat{G} \times \hat{G}/H^\perp \to E$ such that

(i) $f$ is weakly $(\mu_G \otimes \nu)$-measurable;

(ii) for all $h \in H$,

$$f(gh, \hat{x}) = (\hat{x}, h) f(g, \hat{x}) \quad \forall (g, \hat{x}) \in \hat{G} \times \hat{G}/H^\perp;$$

(iii)

$$\int_{\hat{G}/H^\perp} \|f(gh, \hat{x})\|^2_E d(\mu_G(gh) \otimes \nu)(\hat{x}) < +\infty.$$

We identify functions in $\mathcal{H}^\nu$ that are equal $(\mu_G \otimes \nu)$-a.e.. Let $G$ act on $\mathcal{H}^\nu$ as

$$(\lambda^\nu(a)f)(g, \hat{x}) := f(a^{-1}g, \hat{x}), \quad (g, \hat{x}) \in G \times \hat{G}/H^\perp,$$

for all $a \in G$. Define

$$(M^\nu_0(\omega)f)(g, \hat{x}) := \omega(\hat{x}) f(g, \hat{x}), \quad (g, \hat{x}) \in G \times \hat{G}/H^\perp$$

for all $f \in \mathcal{H}^\nu$, $\omega \in C_c(G/H)$.

One can easily prove the following fact.

**Proposition 2:** The space $\mathcal{H}^\nu$ is a Hilbert space with respect to the inner product

$$(f_1, f_2)_{\mathcal{H}^\nu} = \int_{\hat{G}/H^\perp} \langle f_1(g, \hat{x}), f_2(g, \hat{x}) \rangle_E d(\mu_G(gh) \otimes \nu)(\hat{x}).$$

If $\varphi \in C_c(G \times \hat{G}/H^\perp; E)$, let

$$f_\varphi(g, \hat{x}) := \int_{\hat{G}/H^\perp} \langle \varphi(gh, \hat{x}) \rangle_E d\mu_G(gh) \quad \forall (g, \hat{x}) \in G \times \hat{G}/H^\perp.$$

Then $f_\varphi$ is a continuous function in $\mathcal{H}^\nu$ such that $(q \times \text{id}_{\hat{G}/H^\perp})(\text{supp } f_\varphi)$ is compact, and the set

$$\mathcal{H}^\nu_0 = \{f_\varphi | \varphi \in C_c(G \times \hat{G}/H^\perp; E)\}$$

is a dense subspace of $\mathcal{H}^\nu$. The couple $(\lambda^\nu, M^\nu_0)$ is the imprimitivity system induced by $\sigma^\nu$ from $H$ to $G$.

We now diagonalize the representation $\lambda^\nu$. First of all, we let $\nu$ be the measure defined in $\hat{G}$ by Eq. (1). Let $\Lambda^\nu$ be the diagonal representation of $G$ acting on $L^2(\hat{G}, \nu; E)$ as
Due to the properties of \( S \),

\[
(\Lambda^v(g)\phi)(x) = \langle x, g \rangle \phi(x), \quad x \in \mathcal{G},
\]

for all \( g \in G \).

Moreover, given \( \phi: \mathcal{G} \rightarrow E \) and fixed \( x \in \mathcal{G} \), define \( \phi_x \) from \( H^\perp \) to \( E \) as

\[
\phi_x(y) = \phi(xy) \quad \forall y \in H^\perp.
\]

**Theorem 3:** There is a unique unitary operator \( \Sigma \) from \( \mathcal{H}^\perp \) onto \( L^2(\mathcal{G}, \nu; E) \) such that, for all \( f \in \mathcal{H}^\perp_0 \),

\[
(\Sigma f)(x) = \int_{G/H} \langle x, g \rangle f(g, \hat{x}) d\mu_{G/H}(\hat{g}), \quad x \in \mathcal{G}.
\]

The operator \( \Sigma \) intertwines \( \lambda^v \) with \( \Lambda^v \). Moreover,

\[
(\Sigma^v \varphi)(g, \hat{x}) = \int_{H^\perp} \overline{\varphi(xy)} d\mu_{H^\perp}(y), \quad (g, \hat{x}) \in G \times \hat{H},
\]

for all \( \varphi \in C_c(\mathcal{G}; E) \).

**Proof:** We first define \( \Sigma \) on \( \mathcal{H}^\perp_0 \). Let \( f \in \mathcal{H}^\perp_0 \). Fix \( x \in \mathcal{G} \). By virtue of Eq. (2) the function

\[
g \mapsto \langle x, g \rangle f(g, \hat{x})
\]

depends only on the equivalence class \( \hat{g} \) of \( g \) and we let \( f^x \) be the corresponding map on \( G/H \). Due to the properties of \( f \), \( f^x \) is continuous and has compact support, so it is \( \mu_{G/H} \)-integrable and we define \( \Sigma f \) by means of Eq. (3).

We claim that \( \Sigma f \) is in \( L^2(\mathcal{G}, \nu; E) \) and \( \| \Sigma f \|_{L^2(\mathcal{G}, \nu; E)} = \| f \|_{\mathcal{H}^\perp} \). Since the map

\[
(\hat{g}, \hat{x}) \mapsto f^x(\hat{g})
\]

is continuous, by a standard argument \( \Sigma f \) is continuous. Moreover, if \( x \in \mathcal{G} \) and \( y \in H^\perp \),

\[
(\Sigma f)(xy) = \int_{G/H} \langle xy, g \rangle f(g, \hat{x}) d\mu_{G/H}(\hat{g}) = \int_{G/H} \langle \hat{x}, \hat{g} \rangle \langle x, g \rangle f(g, \hat{x}) d\mu_{G/H}(\hat{g}) = \mathcal{F}_{G/H}(f^x)(y).
\]

Indeed,

\[
\| \Sigma f \|_{L^2(\mathcal{G}, \nu; E)}^2 = \int_{\mathcal{G}} \| \Sigma f(x) \|_{\nu}^2 d\nu(x)
\]

\[
= \int_{G/H^\perp} \nu(\hat{x}) \int_{H^\perp} \| (\Sigma f)(xy) \|_{\nu}^2 d\mu_{H^\perp}(y)
\]

\[
= \int_{G/H^\perp} \nu(\hat{x}) \int_{H^\perp} \| \mathcal{F}_{G/H}(f^x)(y) \|_{\nu}^2 d\mu_{H^\perp}(y) \quad \text{(unitarity of } \mathcal{F}_{G/H})
\]

\[
= \int_{G/H^\perp} \nu(\hat{x}) \int_{G/H} \| f^x(\hat{g}) \|_{\nu}^2 d\mu_{G/H}(\hat{g})
\]

\[
= \int_{G/H^\perp} \nu(\hat{x}) \int_{G/H} \| f(g, \hat{x}) \|_{\nu}^2 d\mu_{G/H}(\hat{g})
\]

\[
= \int_{G/H \times G/H^\perp} \| f(g, \hat{x}) \|_{\nu}^2 d(\mu_{G/H} \otimes \nu)(\hat{g}, \hat{x})
\]

\[
= \| f \|_{\mathcal{H}^\perp}^2.
\]
By density, $\Sigma$ extends to an isometry from $\mathcal{H}^v$ to $L^2(\hat{G}, \tilde{\nu}; E)$. Clearly, Eq. (3) holds and it defines uniquely $\Sigma$.

The second step is computing the adjoint of $\Sigma$. Let $\varphi \in C_c(\hat{G}; E)$. By standard arguments the right hand side of Eq. (4) is a continuous function of $(g, \hat{\chi})$. Moreover, it satisfies Eq. (2). We have

$$\int_{\mathcal{H}^v} \langle xy, g \rangle \varphi(xy) d\mu_H - (y) = \langle \overline{xy}, \varphi_\chi \rangle_{L^2} \mathcal{F}_{\mathcal{G}H}(\varphi_\chi) \hat{g}, \quad (g, \hat{\chi}) \in G \times \hat{H}.$$  

First of all, we show that the above function is in $\mathcal{H}^v$. Indeed,

$$\int_{G\hat{H}^v} d\nu(\hat{\chi}) \int_{G\hat{H}} \|\langle x, g \rangle \mathcal{F}_{\mathcal{G}H}(\varphi_\chi) \hat{g}\|_{L^2}^2 d\mu_{G\hat{H}}(\hat{g})$$  

$$= \int_{G\hat{H}^v} d\nu(\hat{\chi}) \int_{G\hat{H}} \|\mathcal{F}_{\mathcal{G}H}(\varphi_\chi) \hat{g}\|_{L^2}^2 d\mu_{G\hat{H}}(\hat{g}) \quad \text{(unitarity of $\mathcal{F}_{\mathcal{G}H}$)}$$  

$$= \int_{G\hat{H}^v} d\nu(\hat{\chi}) \int_{H^v} \|\varphi_\chi(y)\|_{L^2}^2 d\mu_H - (y)$$  

$$= \int_{G\hat{H}^v} d\nu(\hat{\chi}) \int_{H^v} \varphi(xy)^2 d\mu_H - (y)$$  

$$= \|\varphi\|_{L^2(G\hat{H}; E)}^2. \quad (5)$$

Moreover, for all $f \in \mathcal{H}^v_0$, we have

$$\langle \Sigma^* \varphi, f \rangle_{\mathcal{H}^v} = \langle \varphi, \Sigma f \rangle_{L^2(G\hat{H}; \tilde{\nu}; E)}$$  

$$= \int_{G\hat{H}^v} d\nu(\hat{\chi}) \int_{H^v} \varphi(xy) \langle \Sigma f(xy) \rangle_{L^2} d\mu_H - (y)$$  

$$= \int_{G\hat{H}^v} d\nu(\hat{\chi}) \int_{H^v} \varphi(xy) \mathcal{F}_{\mathcal{G}H}(f)(y) d\mu_H - (y) \quad \text{(unitarity of $\mathcal{F}_{\mathcal{G}H}$)}$$  

$$= \int_{G\hat{H}^v} d\nu(\hat{\chi}) \int_{G\hat{H}} \mathcal{F}_{\mathcal{G}H}(\varphi_\chi) \hat{g}, f \hat{g} d\mu_{G\hat{H}}(\hat{g})$$  

$$= \int_{G\hat{H}^v} d\nu(\hat{\chi}) \int_{G\hat{H}} \mathcal{F}_{\mathcal{G}H}(\varphi_\chi) \hat{g}, f \hat{g} d\mu_{G\hat{H}}(\hat{g})$$  

$$= \int_{G\hat{H}^v \times G\hat{H}} \langle \overline{\langle x, g \rangle \mathcal{F}_{\mathcal{G}H}(\varphi_\chi) \hat{g}, f \hat{g} \rangle_{L^2} \rangle d(\mu_{G\hat{H}} \otimes \nu)(\hat{g}, \hat{\chi}).$$

Since $\mathcal{H}^v_0$ is dense, Eq. (4) follows. By Eq. (5) $\Sigma^*$ is isometric, hence $\Sigma$ is unitary.

Finally, we show the intertwining property. Let $a \in G$ and $f \in \mathcal{H}^v_0$. Then $\lambda^v(a) f \in \mathcal{H}^v_0$, and so one has
Here and in the following, convolutions are always taken in $H$ which is well defined and continuous. Moreover, for all $x \in \hat{G}$, hence Eq. (3) holds on $C_c(\hat{G}; E)$.

By density of $\mathcal{H}_0^\perp$, it follows that $\Sigma \lambda^a(a) = \Lambda^a(a) \Sigma$.

Given $\omega \in C_c(G/H)$, let $M^\ast_0(\omega) = \Sigma M^\ast_0(\omega) \Sigma^\ast$. Then we have the following proposition.

**Proposition 4:** For all $\omega \in C_c(G/H)$ and $\phi \in L^2(\hat{G}, \tilde{\nu}; E)$,

$$\langle \tilde{M}^\ast_0(\omega) \phi \rangle(x) = \int_{H^\perp} \mathcal{F}_{G/H}(\omega)(y) \phi(xy^{-1}) d\mu_{H^\perp}(y), \quad x \in \hat{G}. \quad (6)$$

**Proof:** Let $\omega \in C_c(G/H)$. We compute the action of $\tilde{M}^\ast_0(\omega)$ on $C_c(\hat{G}; E)$. If $\varphi \in C_c(\hat{G}; E)$, let

$$\xi(x) := \int_{H^\perp} \mathcal{F}_{G/H}(\omega)(y) \varphi(xy^{-1}) d\mu_{H^\perp}(y) \quad \forall x \in \hat{G},$$

which is well defined and continuous. Moreover, for all $x \in \hat{G}$ and $y \in H^\perp$,

$$\xi(xy) = \int_{H^\perp} \mathcal{F}_{G/H}(\omega)(y') \varphi(xy'y^{-1}) d\mu_{H^\perp}(y')$$

$$= \int_{H^\perp} \mathcal{F}_{G/H}(\omega)(y') \varphi(y'xy^{-1}) d\mu_{H^\perp}(y') = \langle \mathcal{F}_{G/H}(\omega) \ast \varphi \rangle(y). \quad (7)$$

Here and in the following, convolutions are always taken in $H^\perp$. If $\varphi, \psi \in C_c(\hat{G}; E)$,

$$\langle \tilde{M}^\ast_0(\omega) \varphi, \psi \rangle_{L^2(\hat{G}, \tilde{\nu}; E)} = \langle M^\ast_0(\omega) \Sigma \ast \varphi, \Sigma \ast \psi \rangle_{H^\perp}$$

$$= \int_{G/H^\perp} d\nu(\dot{x}) \int_{G/H} d\mu_{G/H}(\dot{g})$$

$$\times \langle \omega(\dot{g})(x, \dot{x}) \mathcal{F}^\ast_{G/H}(\varphi, \psi)(x, \dot{x}) \rangle_E$$

$$= \int_{G/H^\perp} d\nu(\dot{x}) \int_{G/H} d\mu_{G/H}(\dot{g}) \langle \omega(\dot{g}) \mathcal{F}^\ast_{G/H}(\varphi, \psi)(x, \dot{g}) \rangle_E$$

$$\times (\dot{g})_E \text{ (unitarity of } \mathcal{F}_{G/H} \text{ and properties of convolution)}$$

$$= \int_{G/H^\perp} d\nu(\dot{x}) \int_{H^\perp} d\mu_{H^\perp}(y) \langle (\mathcal{F}^\ast_{G/H}(\omega) \ast \varphi)(y), \psi(y) \rangle_E$$

$$= \int_{G/H^\perp} d\nu(\dot{x}) \int_{H^\perp} d\mu_{H^\perp}(y) \langle \xi(xy), \psi(xy) \rangle_E,$$

hence Eq. (6) holds on $C_c(\hat{G}; E)$.

Let now $\phi \in L^2(\hat{G}, \tilde{\nu}; E)$. Since
by virtue of the Fubini theorem there is a \( \nu \)-negligible set \( Y_1 \subseteq \hat{G}/H^\perp \) such that, for all \( x \in \hat{G} \) with \( \hat{x} \in Y_1 \), \( \phi_x \in L^2(\hat{H}^\perp, \mu_{\hat{H}^\perp}; E) \). Moreover, using the definition of \( \tilde{\nu} \), one can check that \( \tau^{-1}(Y_1) \) is \( \tilde{\nu} \)-negligible. Then, for \( \tilde{\nu} \)-almost all \( x \in \hat{G} \), \( \phi_x \) is in \( L^2(\hat{H}^\perp, \mu_{\hat{H}^\perp}; E) \). We observe that the map

\[
\tilde{g} \mapsto \omega(\tilde{g})(\bar{\mathcal{F}}_{G/H}^\pm(\phi_x))(\tilde{g})
\]

is then in \( (L^1 \cap L^2)(\hat{G}/H, \mu_{G/H}; E) \) for \( \tilde{\nu} \)-almost all \( x \in \hat{G} \), hence its Fourier cotransform is continuous, and we have

\[
\bar{\mathcal{F}}_{G/H}(\omega \bar{\mathcal{F}}_{G/H}^\pm(\phi_x))(e) = (\bar{\mathcal{F}}_{G/H}(\omega) \phi_x)(e) = \int_{\hat{H}^\perp} \bar{\mathcal{F}}_{G/H}(\omega)(y) \phi(xy^{-1})d\mu_{\hat{H}^\perp}(y).
\]  

(8)

Now, we let \( (\phi_k)_k \) be a sequence in \( C_1(\hat{G}; E) \) converging to \( \phi \) in \( L^2(\hat{G}, \tilde{\nu}; E) \). Then

\[
\int_{\hat{G}/H^\perp} d\nu(\hat{x}) \int_{\hat{H}^\perp} \|\phi_k(x) - \phi_x(y)\|^2 d\mu_{\hat{H}^\perp}(y) \to 0
\]

and so, possibly passing to a subsequence, there is a \( \nu \)-negligible set \( Y_2 \subseteq \hat{G}/H^\perp \) such that

\[
\int_{\hat{H}^\perp} \|\phi_k(x) - \phi_x(y)\|^2 d\mu_{\hat{H}^\perp}(y) \to 0
\]

for all \( x \in \hat{G} \) with \( \hat{x} \in Y_2 \). This fact means that, for \( \tilde{\nu} \)-almost all \( x \in \hat{G} \),

\[
(\phi_k)_k \to \phi
\]

in \( L^2(H^\perp, \mu_{H^\perp}; E) \). It follows that

\[
\omega \bar{\mathcal{F}}_{G/H}^\pm((\phi_k)_k) \to \omega \bar{\mathcal{F}}_{G/H}^\pm(\phi_x)
\]

in \( L^1(\hat{G}/H, \mu_{G/H}; E) \). Then, for \( \tilde{\nu} \)-almost all \( x \in \hat{G} \),

\[
\bar{\mathcal{F}}_{G/H}(\omega \bar{\mathcal{F}}_{G/H}^\pm((\phi_k)_k)) \to \bar{\mathcal{F}}_{G/H}(\omega \bar{\mathcal{F}}_{G/H}^\pm(\phi_x))
\]

uniformly, and, using Eqs. (7), and (8),

\[
(\tilde{M}_0(\omega) \phi_k)(x) = \bar{\mathcal{F}}_{G/H}(\omega \bar{\mathcal{F}}_{G/H}^\pm((\phi_k)_k))(e) \to \bar{\mathcal{F}}_{G/H}(\omega \bar{\mathcal{F}}_{G/H}^\pm(\phi_x))(e) = \int_{\hat{H}^\perp} \bar{\mathcal{F}}_{G/H}(\omega)(y) \phi(xy^{-1})d\mu_{\hat{H}^\perp}(y).
\]

Since \( \tilde{M}_0(\omega) \phi_k \) converges to \( \tilde{M}_0(\omega) \phi \) in \( L^2(\hat{G}, \tilde{\nu}; E) \), Eq. (6) follows from unicity of the limit.

\[\blacksquare\]

IV. CHARACTERIZATION OF COVARIANT POVMs

We fix in the following an infinite dimensional Hilbert space \( E \). According to the results of the previous sections, the generalized imprimitivity theorem for Abelian groups can be stated in the following way.

**Theorem 5:** A POVM \( M \) based on \( G/H \) and acting on \( \mathcal{H} \) is covariant with respect to \( U \) if and only if there exist a measure \( \nu \) on \( \hat{G}/H^\perp \) and an isometry \( W \) intertwining \( U \) with \( \Lambda^\nu \) such that...
for all \( \omega \in \mathcal{C}_c(G/H) \).

To get an explicit form of \( W \), we assume that \( U \) acts diagonally on \( \mathcal{H} \). This means that \( \mathcal{H} \) is the orthogonal sum of invariant subspaces

\[
\mathcal{H} = \bigoplus_{k \in I} L^2(\hat{G}, \rho_k; F_k),
\]

where \( I \) is a denumerable set, \( (\rho_k)_{k \in I} \) is a family of measures on \( \hat{G} \), \( (F_k)_{k \in I} \) is a family of Hilbert spaces, and the action of \( U \) is given by

\[
(U(g)\phi_k)(x) = \langle x, g \rangle \phi_k(x), \quad x \in \hat{G},
\]

where \( \phi_k \in L^2(\hat{G}, \rho_k; F_k) \) and \( g \in G \). We will denote by \( P_k \) the orthogonal projector onto the subspace \( L^2(\hat{G}, \rho_k; F_k) \).

The assumption (9) is not restrictive. Indeed, it is well known that there are a family of disjoint measures \( (\rho_k)_{k \in I} \) and a family of Hilbert spaces \( (F_k)_{k \in I} \) such that \( \dim F_k = k \) and, up to a unitary equivalence, Eq. (9) holds.

Given the decomposition (9), let \( \rho \) be a measure on \( \hat{G} \) such that

\[
\rho(N) = 0 \Leftrightarrow \rho_k(N) = 0 \quad \forall k \in I.
\]

We recall that the equivalence class of \( \rho \) is uniquely defined by the family \( (\rho_k)_{k \in I} \).

Finally, we observe also that the equivalence class of \( \rho \) is independent of the choice of decomposition (9). Indeed, if \( G \) acts diagonally on another decomposition,

\[
\mathcal{H} = \bigoplus_{k \in I'} L^2(\hat{G}, \rho'_k; F'_k),
\]

then

\[
\rho'_k(N) = 0 \quad \forall k \in I' \Leftrightarrow \rho_k(N) = 0 \quad \forall k \in I.
\]

It follows that the representation \( U \) defines uniquely an equivalence class \( \mathcal{C}_U \) of measures \( \rho \) such that relation (10) holds. Chosen in this equivalence class a finite measure \( \rho \), we denote by \( \mathcal{C}_U^\infty \) the equivalence class of the image measure \( \rho^\infty \). Clearly \( \mathcal{C}_U^\infty \) depends only on \( \mathcal{C}_U \).

We now give the central result of this section.

**Theorem 6:** Let \( U \) be a representation of \( G \) acting diagonally on

\[
\mathcal{H} = \bigoplus_{k \in I} L^2(\hat{G}, \rho_k; F_k).
\]

Given \( \nu_U \in \mathcal{C}_U^\infty \), let \( \tilde{\nu}_U \) be the measure given by Eq. (1). The representation \( U \) admits covariant positive operator valued measures based on \( G/H \) if and only if, for all \( k \in I \), \( \rho_k \) has density with respect to \( \tilde{\nu}_U \). In this case, for every \( k \in I \), let \( \alpha_k \) be the densities of \( \rho_k \) with respect to \( \tilde{\nu}_U \).

Let \( E \) be a fixed infinite dimensional Hilbert space. For each \( k \in I \), let

\[
\hat{\rho}_k \equiv x \mapsto W_k(x) \in \mathcal{L}(F_k; E)
\]

be a weakly measurable map such that \( W_k(x) \) are isometries for \( \rho_k \)-almost all \( x \in \hat{G} \). For \( \omega \in \mathcal{C}_c(G/H) \), let \( M(\omega) \) be the operator given by
\[(P_j M(\omega) P_k \phi)(x) = \int_{H^+} d\mu_{H^+}(y) \overline{F_{GiH}}(\omega)(y) \frac{\sqrt{\alpha_j(xy^{-1})}}{\alpha_j(x)} \times W_j(x)^* W_k(xy^{-1})(P_k \phi)(xy^{-1}), \quad x \in \hat{G}, \quad (11)\]

for all \( \phi \in \mathcal{H} \) and \( k, j \in I \). Then, \( M \) is a POVM covariant with respect to \( U \).

Conversely, any POVM based on \( G/H \) and covariant with respect to \( U \) is of the form given by Eq. (11).

We add some comments before the proof of the theorem.

Remark 7: We observe that Eq. (11) is invariant with respect to the choice of the measure \( \nu_U \in \mathcal{C}_U^\pi \). Indeed, let \( \nu'_U \in \mathcal{C}_U^\pi \), and \( \beta > 0 \) be the density of \( \nu_U \) with respect to \( \nu'_U \). Clearly,

\[
\tilde{\nu}_U = (\beta \circ \pi) \tilde{\nu}'_U,
\]

so that the densities \( \alpha'_k \) of \( \rho_k \) with respect to \( \tilde{\nu}'_U \) are

\[
\alpha'_k = (\beta \circ \pi) \alpha_k.
\]

It follows that Eq. (11) does not depend on the choice of \( \nu_U \in \mathcal{C}_U^\pi \).

Corollary 8: Let \( H \) be the trivial subgroup \( \{e\} \). The representation \( U \) admits covariant positive operator valued measures based on \( G \) if and only if the measures \( \rho_k \) have densities with respect to the Haar measure \( \mu_\hat{G} \). In this case, the functions \( \alpha_k \) in Eq. (11) are the densities of \( \rho_k \) with respect to \( \mu_\hat{G} \).

Remark 9: The content of the previous corollary was first shown by Holevo in Ref. 11 for non-normalized POVM. In order to compare the two results, observe that, if \( \phi \in (L^1 \cap L^2)(\hat{G}, \rho_k; F_j) \) and \( \psi \in (L^1 \cap L^2)(\hat{G}, \rho_k; F_j) \), Eq. (11) becomes

\[
(M(\omega) \phi, \psi)_H = \int_{\hat{G}} d\mu_{\hat{G}}(g) \omega(g) \int_{\hat{G} \times \hat{G}} \langle x, g \rangle \langle y, g \rangle \sqrt{\alpha_k(y) \alpha_j(x)} \times (W_j(x)^* W_k(y) \phi(y), \phi(x))d(\mu_\hat{G} \otimes \mu_\hat{G})(x, y)
\]

\[
= \int_{\hat{G}} d\mu_{\hat{G}}(g) \omega(g) \int_{\hat{G} \times \hat{G}} K_{\phi, \psi}(x, y) d(\mu_\hat{G} \otimes \mu_\hat{G})(x, y),
\]

where

\[
K_{\phi, \psi}(x, y) = \sqrt{\alpha_k(y) \alpha_j(x)} (W_k(y) \phi(y), W_j(x) \psi(x))
\]

is a bounded positive definite measurable field of forms [compare with Eqs. (4.2) and (4.3) in Ref. 11].

In order to prove Theorem 6, we need the following lemma.

Lemma 10: Let \( \rho \) be a finite measure on \( \hat{G} \). Assume that there is a measure \( \nu \) on \( \hat{G}/H^\perp \) such that \( \rho \) has density with respect to \( \nu \). Then \( \rho \) has density with respect to \( \nu^\pi \). In this case, \( \nu \) uniquely decomposes as

\[
\nu = \nu_1 + \nu_2,
\]

where \( \nu_1 \) is equivalent to \( \rho^\pi \) and \( \nu_2 \perp \rho^\pi \).

Proof: Suppose that \( \nu \) is a measure on \( \hat{G}/H^\perp \) such that \( \rho = \alpha \nu \), where \( \alpha \) is a non-negative \( \nu \)-integrable function on \( \hat{G} \). Then, for all \( \phi \in C_c(\hat{G}/H^\perp) \),

\[
\rho^\pi(\varphi) = \int_{\hat{G}} \varphi(\pi(x)) d\rho(x) = \int_{\hat{G}/H^\perp} d\nu(x) \int_{H^+} \varphi(x) \alpha(xy) d\mu_{H^+}(y) = \int_{\hat{G}/H^\perp} \varphi(x) \alpha'(x) d\nu(x),
\]

\[
\nu_1 = \nu - \nu_2,
\]

where \( \nu_1 \) is equivalent to \( \rho^\pi \) and \( \nu_2 \perp \rho^\pi \).
where the function
\[ \alpha'(x) := \int_{H^2} \alpha(xy) d\mu_{H^2}(y) \geq 0 \]
is \( \nu \)-integrable by virtue of Fubini theorem. It follows that
\[ \rho^\nu = \alpha' \nu. \] (12)

Using the Lebesgue theorem, we can uniquely decompose
\[ \nu = \nu_1 + \nu_2, \]
where \( \nu_1 \) has base \( \rho^\nu \) and \( \nu_2 \perp \rho^\nu \). From Eq. (12), it follows that \( \nu_1 \) and \( \rho^\nu \) are equivalent, and this proves the second statement of the lemma. If \( A, B \subset \hat{\mathcal{B}}(\hat{G}/\hat{H}^\perp) \) are disjoint sets such that \( \nu_2 \) is concentrated in \( A \) and \( \nu_1 \) is concentrated in \( B \), then \( \nu_2 \) and \( \nu_1 \) are respectively concentrated in the disjoint sets \( \tilde{A} = \pi^{-1}(A) \) and \( \tilde{B} = \pi^{-1}(B) \). By definition of \( \rho^\nu \), we also have
\[ \rho(\tilde{A}) = \rho^\nu(A) = 0. \]

Since \( \rho \) has density with respect to \( \tilde{\nu} = \tilde{\nu}_1 + \tilde{\nu}_2 \) and \( \tilde{\nu}_2 \) is concentrated in \( \tilde{A} \), it follows that \( \rho \) has density with respect to \( \tilde{\nu}_1 \equiv \rho^\nu \). The claim is now clear. \( \blacksquare \)

**Proof of Theorem 6:** Let \( \rho \) be a finite measure in \( C_\mathcal{U} \). By virtue of Theorem 5, \( U \) admits a covariant POVM \( \mathcal{M} \) such that there exists a measure \( \nu \) in \( \hat{G}/\hat{H}^\perp \) such that \( U \) is a subrepresentation of \( \Lambda^\nu \) and each measure \( \rho_k \) has density with respect to \( \tilde{\nu} = \rho \) has density with respect to \( \tilde{\nu} \). From Lemma 10, \( U \) admits a covariant POVM if and only if \( \rho \) has density with respect to \( \rho^\nu \). Since \( \rho^\nu \in C_\mathcal{U}^\nu \), the first claim follows.

Let now \( M \) be a covariant POVM. By Theorem 5, there is a measure \( \nu \) on \( \hat{G}/\hat{H}^\perp \) and an isometry \( W \) intertwining \( U \) with \( \Lambda^\nu \) such that
\[ M(\omega) = W^* \tilde{M}_\mathcal{U}(\omega) W \quad \forall \omega \in C_\mathcal{U}(G/H). \]

Using Lemma 10, we (uniquely) decompose
\[ \nu = \nu_1 + \nu_2, \]
where \( \nu_1 \) is equivalent to \( \nu_U \) and \( \nu_2 \perp \nu_U \). Then we have
\[ \sigma^\nu = \sigma^\nu_U \oplus \sigma^\nu_2 = (\Lambda^\nu, \tilde{M}_\mathcal{U}) \equiv (\Lambda^\nu_U, \tilde{M}_\mathcal{U}^U) \oplus (\Lambda^\nu_2, \tilde{M}_\mathcal{U}^2), \]
i.e., the imprimitivity system \((\Lambda^\nu, \tilde{M}_\mathcal{U})\) preserves the decomposition
\[ L^2(\hat{G}, \tilde{\nu}; E) \equiv L^2(\hat{G}, \tilde{\nu}_U; E) \oplus L^2(\hat{G}, \tilde{\nu}_2; E). \]

Moreover, since each \( \rho_k \) has density with respect to \( \tilde{\nu}_U \) and \( \tilde{\nu}_U \) is disjoint from \( \tilde{\nu}_2 \), it follows that \( W(\mathcal{H}) \subset L^2(\hat{G}, \tilde{\nu}_U; E) \), then we can always assume that the measure \( \nu \) on \( \hat{G}/\hat{H}^\perp \) which occurs in Theorem 5 is \( \nu_U \).

We now characterize the form of \( W \). For \( k \in I \), we can always fix an isometry \( T_k : F_k \rightarrow E \) such that \( T_k(F_k) \) are mutually orthogonal subspaces of \( E \). Hence, if we define, for \( \phi_k \in L^2(\hat{G}, \rho_k; F_k) \),
\[ (T\phi_k)(x) := \sqrt{\alpha_k(x)} T_k \phi_k(x), \quad x \in \hat{G}, \]}
where we set
\[ t \text{ isometries for } \Lambda^{x_U} \text{, hence there exists a weakly measurable correspondence } \tilde{G} \ni x \mapsto V(x) \in \mathcal{L}(E) \text{ such that } V(x) \text{ are partial isometries for } \tilde{v}_U \text{-almost all } x \in \tilde{G} \text{ and} \]
\[ (V\phi)(x) = V(x)\phi(x), \quad x \in \tilde{G}, \]
where \( \phi \in L^2(\tilde{G}, \tilde{v}_U; E) \). We have \( W = WT^*T = VT \). Then
\[ (W_k \phi_k)(x) = \sqrt{\alpha_k(x)} V(x)T_k \phi_k(x) = \sqrt{\alpha_k(x)} W_k(x) \phi_k(x), \quad x \in \tilde{G}, \quad (13) \]
where we set
\[ W_k(x) = V(x)T_k \quad \forall x \in \tilde{G}. \]
Since \( W \) is isometric, then \( W_k^*W_k \) is the identity operator on \( L^2(\tilde{G}, \rho_k; F_k) \), hence
\[ T_k^* V(x)^* V(x)T_k = I_k, \quad x \in \tilde{G}, \]
\( \rho_k \)-almost everywhere, where \( I_k \) is the identity operator on \( F_k \). Since \( T_k \) is isometric and \( V(x) \) is a partial isometry for \( \tilde{v}_U \)-almost every \( x \in \tilde{G} \) (that is for \( \rho_k \)-almost every \( x \in \tilde{G} \)), it follows that \( V(x)^* V(x) \) is the identity on \( \text{ran} T_k \) and that \( W_k(x) \) is isometric, for \( \rho_k \)-almost every \( x \in \tilde{G} \). Weak measurability of the maps \( x \mapsto W_k(x) \) is immediate.

The explicit form of \( M \) is then given by
\[ (P_j M(\omega) P_k \phi)(x) = (W_j^* M_j^0(\omega) W_k \phi)(x) = \frac{1}{\sqrt{\alpha_j(x)}} W_j(x)^* \int_{H^*} \overline{F_{G/H}}(\omega)(y) \times \sqrt{\alpha_k(xy^{-1})} W_k(xy^{-1})(P_k \phi)(xy^{-1}) d\mu_H(y), \quad x \in \tilde{G}, \]
where \( \phi \in \mathcal{H}, \quad \omega \in C_c(G/H) \).

Conversely, let \( \tilde{G} \ni x \mapsto W_k(x) \in \mathcal{L}(F_k; E) \) be a weakly measurable map such that \( W_k(x) \) are isometries for \( \rho_k \)-almost every \( x \in \tilde{G} \) and for all \( k \in I \). We define, for \( \phi_k \in L^2(\tilde{G}, \rho_k; F_k) \),
\[ (W_k \phi_k)(x) = \sqrt{\alpha_k(x)} W_k(x) \phi_k(x) \quad \forall x \in \tilde{G}. \]
Then \( W \) is clearly an intertwining isometry between \( U \) and \( \Lambda^{x_U} \) and Eq. (11) defines a covariant POVM. \( \square \)

We now study the problem of equivalence of covariant POVMs. To simplify the exposition, we assume that the measures \( \rho_k \) in decomposition (9) are orthogonal.

Let \( M \) and \( M' \) be two covariant positive operator valued measures that are equivalent, i.e., there exists an unitary operator \( S: \mathcal{H} \to \mathcal{H} \) such that
\[ SU(g) = U(g)S \quad \forall g \in G, \quad (14) \]
\[ SM(\omega) = M'(\omega)S \quad \forall \omega \in C_c(G/H). \quad (15) \]
We have the following result.

Proposition 11: Let \( (W_j)_{j \in I} \) and \( (W'_j)_{j \in I} \) be families of maps such that Eq. (11) holds for \( M \) and \( M' \), respectively.

The POVMs \( M \) and \( M' \) are equivalent if and only if, for each \( k \in I \), there exists a weakly measurable map \( x \mapsto S_k(x) \in \mathcal{L}(F_k) \) such that \( S_k(x) \) are unitary operators for \( \rho_k \)-almost all \( x \) and
\[ \sqrt{\alpha_k(xy)} W_j(x)^* W_k(xy) = \sqrt{\alpha_k(xy)} S_j(x)^* W'_j(xy) S_k(xy) \quad (16) \]
for \((\rho_j \otimes \mu_{H^+})\)-almost all \((x,y)\).

Proof: By virtue of condition (14) and orthogonality of the measures \(\rho_k\), \(S\) preserves decomposition (9). Moreover, for each \(k \in I\), there exists a weakly measurable map \(x \mapsto S_k(x) \in L^2(F_k)\) such that \(S_k(x)\) is unitary for \(\rho_k\)-almost all \(x\) and, if \(\phi_k \in L^2(\hat{G}, \rho_k; F_k)\),

\[(S\phi_k)(x) = S_k(x)\phi_k(x), \quad x \in \hat{G}.
\]

Condition (15) is equivalent to

\[P_j M(\omega) P_k \phi = P_j S^* M'(\omega) SP_k \phi
\]

for all \(\phi \in \mathcal{H}_j, \omega \in C_c(G/H)\) and \(j, k \in I\). It is not restrictive to assume that the densities \(\alpha_k\) are measurable functions. Let

\[\Omega_{j,k}(x,x') = \sqrt{\frac{\alpha_j(x')}{\alpha_j(x)}}(W_j(x)^*W_k(x') - S_j(x)^*W_j'(x)^*W_k'(x')S_k(x')).
\]

Using Eq. (11), the previous condition becomes

\[\int_{H^+} F_{G/H}(\omega)(y) \Omega_{j,k}(x,xy^{-1})(P_k \phi)(xy^{-1})d\mu_{H^+}(y) = 0, \quad (17)
\]

\(\rho_j\)-almost everywhere for all \(\phi \in \mathcal{H}_j, \omega \in C_c(G/H)\) and \(j, k \in I\).

Let \(K\) be a compact set of \(\hat{G}\) and \(v \in F_k\). In Eq. (17) we choose

\[\phi = \chi_K v \in L^2(\hat{G}, \rho_k; F_k)
\]

and \(\omega \in C_c(G/H)\) running over a denumerable subset dense in \(L^2(G/H, \mu_{H^+})\). It follows that there exists a \(\rho_j\)-null set \(N \subset \hat{G}\) such that, for all \(x \not\in N\),

\[\chi_K(xy^{-1}) \Omega_{j,k}(x,xy^{-1})v = 0
\]

for \(\mu_{H^+}\)-almost all \(y \in H^+\). Since \(\Omega_{j,k}\) is weakly measurable, the last equation holds in a measurable subset \(Y \subset \hat{G} \times H^+\) whose complement is a \((\rho_j \otimes \mu_{H^+})\)-null set. Define

\[m(x, y) = xy^{-1} \quad \forall (x, y) \in G^+.
\]

For all \((x,y) \in Y \cap m^{-1}(K)\) we then have

\[\Omega_{j,k}(x,xy^{-1})v = 0.
\]

Since \(F_k\) is separable and \(\hat{G}\) is \(\sigma\)-compact, we get

\[\Omega_{j,k}(x,xy) = 0
\]

for \((\rho_j \otimes \mu_{H^+})\)-almost all \((x,y) \in \hat{G} \times H^+\), that is,

\[\sqrt{\alpha_k(xy)} W_j(x)^*W_k(xy) = \sqrt{\alpha_k(xy)} S_j(x)^*W_j'(x)^*W_k'(xy)S_k(xy)
\]

for \((\rho_j \otimes \mu_{H^+})\)-almost all \((x,y)\).

Conversely, if condition (16) is satisfied for all \(j, k \in I\), then clearly \(M\) is equivalent to \(M'\).
V. EXAMPLES

A. Generalized covariant position observables

Let $\mathcal{H} = L^2(\mathbb{R}, dx)$, where $dx$ is the Lebesgue measure on $\mathbb{R}$. We consider the representation $U$ of the group $\mathbb{R}$ acting on $\mathcal{H}$ as

$$(U(a) \phi)(x) = e^{i a x} \phi(x), \quad x \in \mathbb{R},$$

for all $a \in \mathbb{R}$. By means of Fourier transform, $U$ is clearly equivalent to the regular representation of $\mathbb{R}$. We classify the POVMs based on $\mathbb{R}$ and covariant with respect to $U$. With the notations of the previous sections, we have

$$G = \mathbb{R}, \quad H = \{0\}, \quad G/H = \mathbb{R}, \quad \hat{G} = H^\perp = \mathbb{R}, \quad \hat{G}/H^\perp = \{0\}.$$  

We choose $\mu_{G/H} = (1/2) dx$, so that $\mu_{H^\perp} = dx$, and $E = \mathcal{H}$.

The representation $U$ is already diagonal with multiplicity equal to 1, so that in the decomposition (9) we can set $I = \{1\}$, $\rho_1 = dx$, $F_1 = \mathbb{C}$. Hence, by Corollary 8, $U$ admits covariant POVMs based on $\mathbb{R}$ and $a_1 = 1$.

According to Theorem 6, any covariant POVM $M$ is defined in terms of a weakly measurable map $x \rightarrow W_1(x)$ such that $W_1(x)$ is an isometry for every $x \in \mathbb{R}$. This is equivalent to selecting a weakly measurable map $x \rightarrow h(x)$ with $h(x) \in \mathcal{H}$ such that $W_1(x) = h(x)$, $\forall x \in \mathbb{R}$. Explicitly, if $f \in L^2(\mathbb{R}, dx)$,

$$(M(\omega) \phi)(y) = \int \mathcal{F}_\omega(\omega)(x) \langle h_y, x \rangle \phi(y - x) dx$$

$$= \int \mathcal{F}_\omega(\omega)(y - x) \langle h_x, h_y \rangle \phi(x) dx$$

$$= \int \left( \int \mathcal{F}_\omega(\omega)(z) \langle h_x, h_y \rangle \phi(x) \frac{dz}{2\pi} \right) dx, \quad y \in \mathbb{R}.$$ 

B. Generalized covariant phase observables

We give a complete characterization of the covariance systems based on the one-dimensional torus

$$T = \{ z \in \mathbb{C} | |z| = 1 \} = \{ e^{i \theta} | \theta \in [0, 2\pi) \}. $$

We have

$$G = T, \quad H = \{1\}, \quad G/H = T,$$

$$\hat{G} = H^\perp = \{ (T \ni z \rightarrow z^n \in \mathbb{C}) | n \in \mathbb{Z} \} \cong \mathbb{Z}, \quad \hat{G}/H^\perp = \{1\}.$$  

We choose $\mu_{G/H} = (1/2\pi) d \theta = \mu_T$, so that $\mu_{H^\perp}$ is the counting measure $\mu_Z$ on $\mathbb{Z}$.

Let $U$ be a representation of $T$. Since $T$ is compact, we can always assume that $U$ acts diagonally on

$$\mathcal{H} = \bigoplus_{k=1}^\infty F_k,$$
where $ICZ$, and $F_k$ are Hilbert spaces such that $\dim F_k$ is the multiplicity of the representation $k \in Z$ in $U$. Explicitly,

$$(U(z) \phi_k) = z^k \phi_k$$

for all $z \in T$ and $\phi_k \in F_k$.

In order to use Eq. (9), we notice that $F_k = L^2(Z, \delta_k; F_k)$ (where $\delta_k$ is the Dirac measure at $k$), so that $\rho_k = \delta_k$. By Corollary 8, one has that $U$ admits covariant POVMs based on $T$ and that $\alpha_k(j) = \delta_{kj}$ (where $\delta_{kj}$ is the Kronecker delta).

Choose an infinite dimensional Hilbert space $E$ and, for each $k \in I$, fix an isometry $W_k$ from $F_k$ to $E$. The corresponding covariance system is given by

$$P_j M(\omega) P_k \phi = \mathcal{F}_j(\omega)(j-k) W_k^* W_k \phi = \frac{1}{2\pi} \int_0^{2\pi} \omega(e^{i\theta}) e^{i(j-k)\theta} W_k^* W_k \phi d\theta,$$

where $\phi \in H$ and $\omega \in C(T)$.

If $I = Z$ and $\dim F_k = 1 \forall k \in Z$, $U$ is the number representation and $M$ represents the phase observable (compare with the result obtained in Ref. 3).

**C. Covariant phase difference observables**

Let $\mu_T$ as in the previous section. We consider the following representation $U$ of the direct product $G = T \times T$ acting on the space $\mathcal{H} = L^2(T \times T, \mu_T \otimes \mu_T)$ as

$$(U(a,b)f)(z_1,z_2) = f(a z_1, b^{-1} z_2), \quad (z_1,z_2) \in T \times T,$$

for all $(a,b) \in T \times T$.

Let $H$ be the closed subgroup

$$H = \{(a,b) \in T \times T | b = a\} \equiv T.$$

We classify all the POVMs based on $G/H$ and covariant with respect to $U$ (for a different approach to the same problem, see Ref. 9).

We have

$$G = T \times T, \quad G/H \equiv T, \quad \hat{G} = \hat{T} \times \hat{T} \equiv Z \times Z,$$

$$H^\perp = \{(j,k) \in Z \times Z | k = -j\} \equiv Z,$$

$$\hat{G}/H^\perp \equiv Z.$$

We fix $\mu_{G/H} = \mu_T$, so that $\mu_H = \mu_Z$.

We choose the following orthonormal basis $(e_{i,j})_{i,j \in Z}$ of $\mathcal{H}$,

$$e_{i,j}(z_1, z_2) = z_1^i z_2^{-j}, \quad (z_1, z_2) \in T \times T,$$

so that

$$U(a,b) e_{i,j} = a^i b^j e_{i,j} \quad \forall (a,b) \in T \times T.$$

Let $F_{i,j} = \mathcal{L} e_{i,j}$. Then $U$ acts diagonally on $F_{i,j}$ as the character $(i,j) \in Z \times Z$. Then, one can choose as decomposition (9)

$$\mathcal{H} = \bigoplus_{i,j \in Z} F_{i,j} \equiv \bigoplus_{i,j \in Z} L^2(Z \times Z, \delta_i \otimes \delta_j; F_{i,j}).$$
With the notations of Sec. IV, we have $I = \mathbb{Z} \times \mathbb{Z}$ and $\rho_{i,j} = \delta_i \otimes \delta_j$. It follows that $C^\gamma_{F_i}$ is the equivalence class of $\mu_{Z_i}$. With the choice $\nu_{U} = \mu_{Z_i}$, it follows that $\tilde{\nu} = \mu_{Z_i} \otimes \mu_{Z_j}$. According to Theorem 6, $U$ admits covariant POVMs and $\alpha_{i,j}(n,m) = \delta_{n_i} \delta_{m_j}$. With the choice $E = \mathcal{H}$, we select a map $(i,j) \mapsto W_{i,j}$, where $W_{i,j}$ is an isometry from $F_{i,j}$ to $\mathcal{H}$. Since $F_{i,j}$ are one dimensional, there exists a family of vectors $(h_{i,j})_{i,j} \in \mathcal{H}$, with $\|h_{i,j}\|_{\mathcal{H}} = 1$ such that $W_{i,j} e_{i,j} = h_{i,j}$, $\forall (i,j) \in \mathbb{Z} \times \mathbb{Z}$.

The corresponding covariant POVM $M$ is given, for every $\phi \in \mathcal{H}$, by

$$P_{l,m}M(\omega)P_{l,m} = \sum_{h \in \mathbb{Z}} \mathcal{F}_{\gamma}(\omega)(h) \delta_{h,l} \delta_{m,h,j} \langle h_{i,j}, h_{l,m} \rangle \langle \phi, e_{i,j} \rangle e_{l,m}$$

$$= \delta_{l+m,i+j} \mathcal{F}_{\gamma}(\omega)(j-m) \langle h_{i,j}, h_{l,m} \rangle \langle \phi, e_{i,j} \rangle e_{l,m}.$$ 

In particular, if $l + m = i + j$, we have

$$\langle M(\omega) e_{i,j}, e_{l,m} \rangle = \mathcal{F}_{\gamma}(\omega)(j-m) \langle h_{i,j}, h_{l,m} \rangle = \frac{1}{2\pi} \int_0^{2\pi} \omega(e^{i\theta}) e^{i(j-m)\theta} \langle h_{i,j}, h_{l,m} \rangle d\theta.$$ 

If $l + m \neq i + j$, one has $\langle M(\omega) e_{i,j}, e_{l,m} \rangle = 0$.