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Autor: Löffelholz, J.
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Non-existence of path space measure for local (QED)₁*

By J. Löffelholz

Karl Marx University, Department of Physics/NTZ, 7010 Leipzig, Germany

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Abstract. We study the interaction of a “charged” particle with an oscillator. On the classical level holds $m\dot{x} = p - eA$, where $x, A \in \mathbb{R}$. In QM we let x move on the circle S to have a proper ground state. The imaginary time Green’s functions exist, satisfy OS-like axioms and, for $e \neq 0$, are complex valued. They define a normalized quasimeasure $d\lambda$ on path space $Q \times A$. Our main result is the proof of $\|\lambda\| = +\infty$, due to a theorem of Yngvason. Integrating out the oscillator variable A we find some probability measure $d\mu$ on Q (given by the effective action for the particle). Because of memory it allows us to recover the Hamiltonian semigroup for the coupled quantum system.

1. Introduction

On a heuristic level the idea of path integral was introduced by Feynman [1]. After reformulation of QFT in terms of Euclidean Green’s functions [2] its existence became a challenge for mathematicians [3].

In particular Yngvason [4] obtained the following result: Given those Green’s functions then strong OS-positivity implies that a measure exists and must be real. He used an argument of Fröhlich. However from QED we know that the interaction of charged matter with gauge fields is given by a complex phase factor and, if Θ denotes time reflection, one has combined $PC\Theta$ -symmetry. To understand the crux we looked for some caricature of electromagnetism in standard QM avoiding any troubles with Fermions [5].

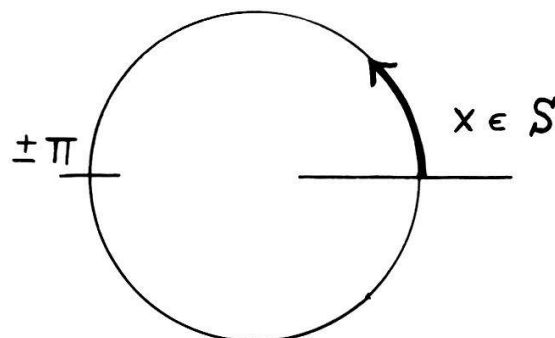


Fig. 1.

*) Seminar given at the Workshop “white noise analysis: New results and their impact on quantum physics”, ZiF Bielefeld Sept. 24–29, 1990

Let x be the angular coordinate of a particle moving on the circle as drawn above. The stationary states of the system are described by eigenfunctions $\Psi = \exp\{i \cdot (kx)\}$, $k \in \mathbb{Z}$, of $p = -id/dx$. Indeed imposing periodic boundary conditions at $x = \pm\pi$ the momentum p defines a selfadjoint operator [6] in $L^2(S)$. When x couples to a homogeneous magnetic field of flux $\Phi = 2\pi A$ then p acquires a shift by $\alpha = eA$, where e was the charge. We claim that for $\alpha \notin \mathbb{Z}$ (otherwise the effect would be invisible) the propagator leads to a complex-valued normalized cylinder measure $d\omega_\alpha$ of infinite total variation [7].

So contrary to general believe the formal substitution $t \rightarrow -it$ does not resolve all problems with the path integral.

2. Model

Below we consider $A \in \mathbb{R}$ as dynamical degree of freedom describing a quantum oscillator. On the classical level our model is given by the coupled equations of motion

$$\left. \begin{aligned} m\ddot{x} &= eE \\ \ddot{A} + \beta^2 A &= e\dot{x} \end{aligned} \right\} \quad (1)$$

where $E = -\dot{A}$. Clearly, $p = m\dot{x} + eA$ and total energy H are conserved. We will fix m equal to one. In QM we realize

$$H = \frac{(p - eA)^2}{2} + I_\beta(E, A), \quad (2)$$

where $I_\beta = 1/2(E^2 + \beta^2 A^2)$, as a Hermitean operator in the separable Hilbert space $\mathcal{H} = L^2(S \times \mathbb{R})$. Of course $p \in \mathbb{Z}$ so that H has discrete spectrum and a proper ground state Ω . The variable $x \in S$ gives a bounded operator with norm $\|x\| = \pi$. This affects the classical identity $m\dot{x} = p - eA$. Indeed, we find the singular anomalous commutation relations

$$\begin{aligned} L &= px - xp \\ &= i \cdot \sum_{k \neq 0} (-1)^k e^{ikx}, \end{aligned} \quad (3)$$

and hence

$$[H, x] = \frac{1}{2i} \{(p - eA)L + L(p - eA)\}. \quad (4)$$

3. Propagator

To obtain the propagator one may start from the Lagrangean [8], calculate the action along a trajectory $t \rightarrow (x(t), A(t))$, $t_1 \leq t \leq t_2$, and then go to imaginary time. Because of the restriction $x \in S$ this seems to be a doubtful venture. Instead we

rewrite

$$\begin{aligned}
 P^t &= \exp(-tH) \\
 &= \exp\left(\frac{-tp^2}{2M}\right) \cdot V^* K^t V, \quad t \geq 0,
 \end{aligned}
 \tag{5}$$

where $V = \exp\{ie/\gamma^2(pE)\}$, $\gamma = \sqrt{\beta^2 + e^2}$ and M is an effective mass. Moreover we introduced $K_\gamma^t = \exp(-tI\gamma)$, governing the oscillator [9]. The unitary V commutes with momentum p . So if

$$L^2(S \times \mathbb{R}) = \bigoplus_{k \in \mathbb{Z}} \mathcal{H}_k,
 \tag{6}$$

on wave functions $\Psi = \Psi(x, A)$ from some fixed sector \mathcal{H}_k the operator V induces a shift of A to $A_k = A - ek/\gamma^2$. Using Poisson's formula [10] we get

$$P^t = \sum_{l \in \mathbb{Z}} \frac{\exp\left(-\frac{z_l^2}{2\tau}\right)}{\sqrt{2\pi\tau}} \cdot K_\gamma^t(A, B),
 \tag{7}$$

where

$$z_l = (y - x) + i\delta(t) \frac{e(A + B)}{2} + 2\pi l,
 \tag{8}$$

$\tau(t) = \gamma^{-2} \cdot (\beta^2 t + e^2 \delta)$ and $0 \leq \delta(t) \leq 2/\gamma$. Hence, for $e \neq 0$, in the Schrödinger representation the imaginary time propagator of the model $(\text{QED})_1$ is complex-valued. We may hardly associate a genuine stochastic process with trajectories $t \rightarrow (x(t), A(t))$ on path space

$$Q \times A = \times_{t \in (-\infty, \infty)} (S \times \mathbb{R}).
 \tag{9}$$

4. Quasimeasure

Let us renormalize the Hamiltonian so that $H\Omega = 0$ and perform a unitary transformation on $L^2(S \times \mathbb{R})$ which brings the ground state vector Ω into the function equal one.

Then for any $t_0 \leq t_1 \leq t_2 \leq \dots \leq t_n$ the iteration of the propagator defines a normalized complex-valued measure $d\lambda_n(xA, yB)$ on the space $\times_{j=0,1,\dots,n} (S \times \mathbb{R})$. For $n = 1$ we obtain

$$d\lambda_1 = d\rho(xA) \cdot P^\varepsilon(xA, yB) dy dB,
 \tag{10}$$

where $\varepsilon = t_1 - t_0$ and $d\rho = \Omega^2 \cdot dx dA$ is the measure on $S \times \mathbb{R}$ defining the new scalar product in the "physical" Hilbert space. Its extension to some σ -additive measure on $Q \times A$ yields a nontrivial problem. Unfortunately we cannot use [11]. But the simple structure of our model allows us to control the total variation of $d\lambda_n$ in the limit $n \nearrow \infty$, directly.

We return to the situation of a particle x moving on the circle S in presence of magnetic flux Φ . The evolution operator

$$R_\alpha^t = \sum_{k \in \mathbb{Z}} \frac{e^{ik(y-x)}}{2\pi} \cdot \frac{e^{-t(k-\alpha)^2}}{2} \frac{1}{2\pi} \sum_{k \in \mathbb{Z}} \exp \left\{ ik(y-x) - \frac{t}{2}(k-\alpha)^2 \right\}, \quad t \geq 0, \quad (11)$$

satisfies $R_\alpha^t 1 = \exp \left(-\frac{t\alpha^2}{2} \right) \cdot 1$, where $\alpha = e\Phi/2\pi$ and the Chapman equation. Via the Kolmogorov construction we find a normalized cylinder measure $d\omega_\alpha$ on Q . We claim that for given $\varepsilon > 0$

$$Y_\alpha(\varepsilon) = \exp \left(\frac{\varepsilon\alpha^2}{2} \right) \cdot \int_S |R_\alpha^\varepsilon(x, y)| dy \geq 1. \quad (12)$$

Equality holds if and only if $\alpha \in \mathbb{Z}$. By inspection the QM amplitude $(\cos x, R_\alpha^\varepsilon \sin x)$ is not real. We remark that $R_\alpha^\varepsilon(x, y)$ coincides with Jacobi's theta function [12] at $z = (y-x) + i\varepsilon\alpha$ and imaginary time parameter. Using the fact that the value of the integral does not depend on $x \in S$ we get

Lemma.

$$\|\omega_\alpha\|(S \times S^n) = Y_\alpha(\varepsilon)^n, \quad n = 0, 1, 2, \dots \quad (13)$$

For large n the total variation of $d\omega_\alpha$ diverges. Conversely, let us fix $t > 0$, so that $\varepsilon = t/n \searrow +0$ if n tends to infinity. Then from $Y_\alpha(\varepsilon) \leq \exp(\varepsilon\alpha^2/2)$ and translation invariance we conclude that on a finite time interval the total variation stays bounded. We easily check Daletzki's condition. We observe the symmetry $d\omega_\alpha \cdot \Theta = (d\omega_\alpha)^*$. Complex conjugation is equivalent to changing α by $-\alpha$. How our lemma can be applied to the full propagator?

For small $\varepsilon \geq 0$ one may substitute $P^\varepsilon(xA, yB)$ by $R_\alpha^\varepsilon(x, y) \cdot K_\gamma^\varepsilon(A, B)$, with $\alpha = e \cdot (A+B)/2$. In the case $n = 1$ for the total variation of $d\lambda$ on $\times_{j=0,1} (S \times \mathbb{R})$ we obtain approximately

$$\iint_{\mathbb{R}^2} Y_{e(A+B)/2}(\varepsilon) \cdot d\varphi_\gamma(A, B), \quad (14)$$

where $d\varphi_\gamma$ denotes the oscillator measure. Finally we combine the above estimate with $e \cdot (A+B)/2 \notin \mathbb{Z}$, for a.e. $(A, B) \in \mathbb{R}^2$, and the fact that $d\varphi_\gamma$ was normalized. Similarly we proceed when $n = 2, 3, \dots$. Hence $d\lambda$ acquires unbounded total variation. We shortly write $\|\lambda\| = +\infty$.

5. OS-axioms

If $e = 0$ the Hamiltonian is the sum of $P^2/2m$ and I_β . Its ground state is given by the vector $1 \otimes \Omega_\beta \in L^2(S \times \mathbb{R})$, where Ω_β stands for the oscillator vacuum.

At imaginary time we have a two-dimensional Markov process $t \rightarrow (x(t), A(t))$ on the large probability space

$$\left(Q \times A, \sum \times \mathfrak{A}, d\omega_0 \otimes d\varphi_\beta \right). \quad (15)$$

The measure $d\omega_\alpha$, for $\alpha = 0$, describes free Brownian motion in the circle S and $d\varphi_\beta$ governs an Ornstein-Uhlenbeck process. The moments factorize. Using $x \in S$ and the fact that $d\varphi_\beta$ is Gaussian we easily derive the estimate

$$|\langle x(s_1)x(s_2) \cdots x(s_m) \cdots A(t_n) \rangle_0| \leq \pi^m \frac{(n!)^{1/2}}{(2\beta)^n}, \tag{16}$$

valid for $m, n = 0, 1, 2, \dots$. Of course for odd m or n this vanishes. As an exercise let us calculate the correlation function of $d\omega_0$. Expanding $f(x) = x$ in a Fourier series on $(-\pi, \pi)$ we get

$$\langle x(s_1)x(s_2) \rangle_0 = \sum_{k \neq 0} k^{-2} \cdot \exp(-\varepsilon k^2/2), \tag{17}$$

where $\varepsilon = |s_2 - s_1|$. In the limit $\varepsilon \searrow +0$ we recover the variance of the normalized Lebesgue measure $dx/2\pi$ on S .

We denote $x = x(0)$ and $u = dx(t)/dt$. Then by the Feynman-Kac formula $-\langle x \cdot u(\varepsilon) \rangle_0$ for small ε becomes equal to the divergent expression

$$\frac{1}{2}(x\Omega, p^2(x\Omega)) = +\infty. \tag{18}$$

Because of $x \in S$ also in the interacting case the existence of Green's functions is rather trivial. But, as we learned above, their time derivatives are singular at coinciding arguments [13].

Theorem I. *The moments $\langle x(s_1)x(s_2) \cdots x(s_m) \cdots A(t_n) \rangle$, where $m, n = 0, 1, 2, \dots$ of the cylinder measure $d\lambda$ on $Q \times A$ exist and are*

- (i) integrable,
 - (ii) time translation invariant,
 - (iii) OS-positive,
 - (iv) complex for $e \neq 0$.
- (19)

Proof. Within the famous reconstruction theorem of Osterwalder and Schrader (iii) is a consequence of QM \square . We would like to check it looking just at the Green's functions of our model. The idea is simple.

The propagator which defines $d\omega_x$ satisfies $R_x^s(x, y)^* = R_x^s(y, x)$, where $x, y \in S$ and $s \geq 0$. So for any bounded function $f = f(x(s))$ we get

$$\int_Q f^* \cdot \Theta f d\omega_x = \exp(-s\alpha^2) \cdot \|\Psi\|^2 \geq 0, \tag{20}$$

where $\Psi = R_x^s f \in L^2(S)$. We also check the inequality for cylinder functions say $f = f(x(s_1), \dots, x(s_n))$ with s_1, s_2, \dots, s_n in \mathbb{R}_+ . Strong OS-positivity requires it to hold for any exponential function measurable with respect to

$$\Sigma_+ = \sigma\left(\bigcup_{s \geq 0} \Sigma_s\right). \tag{21}$$

We observe that $\sigma(\Sigma_- \cup \Sigma_+) = \Sigma$, where Σ_- is the image of Σ_+ under reflection Θ .

This generalizes to the cylinder measure $d\lambda$. What about Yngvason's result? He proved that the above conditions are not compatible with the existence of $d\lambda$ as a *finite* measure. So the upper bound

$$\frac{1}{Z} \iint_{Q \times A} |x(s_1)x(s_2) \cdots x(s_m) \cdots A(t_n)| d\omega_0 \otimes d\varphi_\beta \tag{22}$$

on the Green's functions, for all $m, n = 0, 1, 2, \dots$, implies $Z = 0$. Indeed the free measure $d\omega_0 \otimes d\varphi_\beta$ is ergodic and hence [14] $d\lambda$ cannot be the perturbation by some phase factor.

6. White noise

We remark that

$$\left\langle \exp \left\{ i \cdot \left(\sum_{j=1}^m k_j x(s_j) \right) \right\} A(t_1) \cdots A(t_n) \right\rangle, \tag{23}$$

for $k_1, k_2, \dots, k_m \in \mathbb{Z}$, has an integral representation with respect to the measure $dx \otimes d\eta(u, A)$, where $t \rightarrow u(t) \in \mathbb{R}$ for $e = 0$ was white noise [15]. More precisely, let us consider the operator

$$C = G_\gamma^{1/2} \begin{bmatrix} \Delta & -ie \\ -ie & 1 \end{bmatrix} G_\gamma^{1/2} \tag{24}$$

in $D = L^2(\mathbb{R}) \oplus L^2(\mathbb{R})$. Above $\Delta = \beta^2 - d^2/dt^2$ and $G_\beta(\cdot, \cdot)$ will denote the kernel of its inverse Δ^{-1} . One easily shows that C defines the covariance of the desired cylinder measure on $U \times A$. Of course the restriction of $d\eta$ to \mathfrak{A} should coincide with $d\varphi_\gamma$. To avoid confusion we introduce another symbol $\langle\langle \cdot \rangle\rangle$ for expectation with respect to $d\eta$. We find

$$\langle\langle u(b)A(a) \rangle\rangle = -ie(b, G_\gamma a), \tag{25}$$

$$\langle\langle (u(b)A(a))^2 \rangle\rangle = -2e^2 \cdot (b, G_\gamma a)^2 + \left(b, \frac{1}{1 + e^2 G_\beta} b \right) (a, G_\gamma a), \tag{26}$$

etc. Provided $|e|^2 \leq \beta^2/2$, the last expression becomes non-negative. We claim that C is a sectorial operator [16] in D with half opening angle $\arctg(e/\beta)$. There is a striking analogy to the path space measure for the bosonized massless Schwinger model $(\text{QED})_2$ [17]. Formally $d\eta$ is given by

$$e^{-z^2/2} dz \otimes d\varphi_\gamma |_{z = u + ieA}. \tag{27}$$

Of course the variable z was nothing but the imaginary time counter part of the canonical momentum $p = m\dot{x} + eA$, where m is fixed to one.

Let $t \rightarrow \xi(t) \in \mathbb{R}$ be one-dimensional Brownian motion mastering at time zero the slalom $\xi(0) \in (-\pi, \pi)$. This defines a Markov process on (X, Ξ, dv) , where X is the space of trajectories and Ξ the σ -algebra generated by cylinder sets.

$$dv = dx \otimes e^{-u^2/2} du, \quad x = \xi(0), \tag{28}$$

is an averaged conditional Wiener measure. If we close $(-\pi, \pi)$ to the circle and consider the real line as covering space [18] of S we may identify periodic sets

$$\pi^{-1}(M) = \bigcup_{l \in \mathbb{Z}} \{\xi \in X: \xi(t) - 2\pi l \in M\}, \tag{29}$$

for Borel M in S and $t \neq 0$, with elements of Σ . In other words π was the canonical projection from \mathbb{R} onto $S = \mathbb{R}/\mathbb{Z}$. The lift π^{-1} in a natural way induces a measure isomorphism. All that generalizes to the coupled system.

Theorem II.

$$d\lambda = dx \otimes d\eta \Big|_{\pi^{-1}(\Sigma \times \mathfrak{R})}. \tag{30}$$

We emphasize that $d\lambda$ is translation invariant whereas the measure $dx \otimes d\eta$ was not [19]. The above redefinition allows us to calculate expectation values as $\langle \exp \{i(kx)\} \cdot A(t) \rangle$, for $k \in \mathbb{Z}$. Integrating over $x \in S$ we obtain $\delta(k)$ and then we are left with a Gaussian. For non-integer k everything becomes more tricky. But “Gott kümmert sich nicht um unsre mathematischen Schwierigkeiten. Er integriert empirisch” [20].

7. Memory

As hidden in the title we have an alternative resolution to the problem of existence of a path space measure for $(\text{QED})_1$. We claim that in the mixed representation where x and E are diagonal the QM propagator $P^t = \exp(-tH)$, $t \geq 0$, is positivity preserving [21].

Indeed given any bounded $f(x, E) \geq 0$, because of $\Omega(x, E) \geq 0$, the vector $\Psi = f \cdot \Omega$ is also represented by a non-negative function in the physical Hilbert space $L^2(S \times \mathbb{R})$. We now apply the factors V, K_γ^t, V^* and $\exp\{-t(p^2/2M)\}$ step by step. V shifts the variable x to $x + eE/\gamma^2$, V^* conversely. With the other two operators there is no trouble. Hence $P^t\Psi(x, E) \geq 0$. In particular this will be true for any $\Psi = (g \otimes 1) \cdot \Omega$ with $g(x) \geq 0, x \in S$. By induction

$$(\Omega, g \otimes 1 e^{-(t_2 - t_1)H} g_2 \otimes 1 \cdots g_n \otimes 1 \cdot \Omega) \geq 0, \tag{31}$$

provided $g_j(x) \geq 0$ for all $j = 1, 2, \dots, n$. Let \mathcal{M} denote the Abelian algebra of those bounded multiplication operators $F = g \otimes 1, \|F\| < \infty$, acting in $L^2(S \times \mathbb{R})$. It is the completion of

$$\mathcal{M}_0 = \{F = e^{ikx} \otimes 1: k \in \mathbb{Z}\} \tag{32}$$

in norm and not maximal [22]. Instead we observe that the vacuum $\Omega = 1 \otimes \Omega_\gamma$ is cyclic for the algebra \mathcal{B}_0 generated by $P^t, t \geq 0$, and the elements of \mathcal{M}_0 . Of course \mathcal{B}_0 is dense in the algebra $\mathcal{B} = \mathcal{B}(L^2(S \times \mathbb{R}))$ of all bounded operators.

We claim that

$$\Psi(t) = P^t(e^{ikx} \otimes 1)\Omega, \tag{33}$$

$t \geq 0$, span \mathcal{H}_k except in the case when $k = 0$. But the vacuum sector N of $L^2(S \times \mathbb{R})$ is spanned by the vectors $\Psi(t) = F^*P^tF\Omega$, $t \geq 0$, with any $F \in \mathcal{M}_0$ different from the unit element. This has a nice consequence.

Theorem III. *The triple*

$$L^2(S \times \mathbb{R}), \mathcal{M}_0, \{P^t, t \geq 0\} \tag{34}$$

together with the vacuum Ω builds a generalized positive semigroup structure. Hence the above QM amplitude define the Fourier transform of a probability measure $d\mu$ on Q .

Proof. See Klein's theorem [23] \square . One can show that $d\mu$ is OS-positive. Given $0 \leq t_1 \leq t_2 \leq \dots \leq t_n$ and $k_j \in \mathbb{Z}$ we find

$$\int_Q \exp \left\{ i \left(\sum_{j=1}^n k_j x(t_j) \right) \right\} d\mu = \delta(k) \cdot \exp \left\{ -\frac{1}{2} \left(\sum_{i,j=1}^n k_i k_j \tau^{ij} \right) \right\}, \tag{35}$$

where

$$\tau^{ij} = \left(h_i, \frac{1}{1 + e^2 \cdot G_\beta} h_j \right), \quad i, j = 1, 2, \dots, n. \tag{36}$$

Here h_j are the indicator functions of time intervals $0 \leq s \leq t_j$, $j = 1, 2, \dots, n$ in $\overline{\mathbb{R}}_+$ and k stands shortly for the sum of all k_j 's. The diagonal elements of the matrix τ^{ij} yield a modified function $t \rightarrow \tau(t)$, $t \geq 0$, satisfying

$$\tau(s + t) = \tau(s) + \tau(t) - \frac{e^2}{\gamma} \cdot \delta(s) \delta(t). \tag{37}$$

Let us introduce $L^2(Q)$ with scalar product given by the measure $d\mu$ and denote R the projection operator onto the subspace $L^2(Q_+)$ of functions which are measurable with respect to Σ_+ .

Then [24]

$$\mathcal{H} = \overline{L^2(Q_+) / \ker W}, \tag{38}$$

where $W = +(R\Theta R)^{1/2}$, can be identified with the physical Hilber space. Since $d\mu$ violates the Markov property \mathcal{H} is larger than $L^2(S)$. Indeed we find an isometry $J: \mathcal{H} \rightarrow \mathcal{H}$ so that

$$\begin{aligned} \Psi(t) &= JWT^t e^{ikx} \otimes 1 \\ &= c(t, k^2) \cdot \exp \{ ik(x + \gamma^{-2} \cdot e\delta(t)E) \} \Omega, \end{aligned} \tag{39}$$

where E was the canonical conjugate to A . For details see [25]. On the classical level the elimination of the “invisible” oscillator leads to the following integro-differential equation

$$m\ddot{x}(t) = -e^2 \left\{ x(t) + y \cdot \int_{t_1}^{t_2} C_\beta(s, t)x(s) ds \right\}. \quad (40)$$

Above $-\beta^2 C_\beta(\cdot, \cdot)$ stands for the periodic Green’s function of the hyperbolic operator $\beta^2 + d^2/dt^2$ on (t_1, t_2) [26]. Of course one may choose other boundary conditions as well.

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