Noninformative Quantum $q$-Priors

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Abstract

We find, in an analysis involving four prior probabilities ($p$'s), that the information-theoretic-based comparative noninformativity test devised by Clarke, and applied by Slater in a quantum setting, yields a ranking ($p_{F,q=1} > p_B > p_{B_{q=1}\text{trunc}} > p_F$) fully consistent with Srednicki’s recently-stated criterion for priors of “biasedness to pure states”. Two of the priors are formed by extending certain metrics of quantum-theoretic interest from three- to four-dimensions — by incorporating the $q$-parameter (nonextensivity/Tsallis index/escort parameter). The three-dimensional metrics are the Bures (minimal monotone) metric over the two-level quantum systems and the Fisher information metric over the corresponding family of Husimi distributions. The priors $p_B$ and $p_F$ are the (independent-of-$q$) normalized volume elements of these metrics, and $p_{F,q=1}$ is the normalized volume element of the $q$-extended Fisher information metric, with $q$ set to 1. While originally intended to similarly be the $q$-extension of the Bures metric, with $q$ then set to 1, the prior $p_{B_{q=1}\text{trunc}}$, actually entails the truncation of the only off-diagonal entry of the extended Bures metric tensor. Without this truncation, the $q$-extended Bures volume element is null, as is also the case in two other quantum scenarios we examine.

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I. INTRODUCTION

Some fifteen years ago, Wootters asserted that “there does not seem to be any natural measure on the set of all mixed states” [1, p. 1375]. He did, however, consider random density matrices with all eigenvalues fixed. He remarked that once “the eigenvalues are fixed, then all the density matrices in the ensemble are related to each other by the unitary group, so it is natural to use the unique unitarily invariant measure to define the ensemble” [1, p. 1375] (cf. [2]).

Arguing somewhat similarly, Srednicki recently proposed that in choosing a prior distribution over density matrices, “we can use the principle of indifference, applied to the unitary symmetry of Hilbert space, to reduce the problem to one of choosing a probability distribution for the eigenvalues of $\rho$. There is, however, no compelling rationale for any particular choice; in particular, we must decide how biased we are towards pure states” [3, p. 6].

In this study, we introduce evidence that Srednicki’s standard of biasedness is, in effect, incorporated into an information-theoretic (“comparative non informativity”) test — originally devised by Clarke [4] — that has previously been applied by Slater to quantum systems [5, 6]. We examine a certain four prior probability distributions, denoted $p_{B,q=1,\text{trunc}}, p_{F,q=1}, p_B$ and $p_F$. The first two are constructed in the framework of nonextensive statistical mechanics [7], being (at least, partial in the case of $p_{B,q=1,\text{trunc}}$) $q$-extensions of the last two, which are normalized volume elements of (classically and quantum) monotone metrics [8]. The ranking in order of decreasing noninformativities that we obtain

$$p_{F,q=1} > p_B > p_{B,q=1,\text{trunc}} > p_F$$

will prove (Fig. 1) to be fully consistent with the Srednicki ordering according to biasedness to pure states.

II. BURES METRIC

The Bures (minimal monotone) metric — the volume element of which we normalize to obtain one ($p_B$) of the four prior probability distributions of principal interest here — yields the statistical distance between neighboring mixed quantum states ($\rho$) [9, 10]. It provides an embedding of the Fubini-Study metric [8, sec. IV], which gives the statistical distance
FIG. 1: Four univariate marginal prior probability distributions in the near-to-pure-state region $r \in [1 - \epsilon, 1]$, where $r$ is the radial coordinate in the Bloch sphere representation of two-level quantum systems, and $r = 1$ corresponds to a pure state. The order of dominance fully complies with that obtained by the information-theoretic-based comparative noninformativity test between neighboring pure quantum states ($|\psi\rangle$) (cf. [11]). Hübner gave an explicit formula for the Bures distance [12, p. 240] (cf. [13]),

$$d_B(\rho_1, \rho_2)^2 = 2 - 2\text{tr}(\rho_1^{1/2}\rho_2\rho_1^{1/2})^{1/2}. \quad (2)$$

Further, he expressed it in infinitesimal form as [12, eq. (10)]

$$d_B(\rho, \rho + d\rho)^2 = \sum_{ij} \frac{1}{4} \frac{|i\rangle\langle j|}{\lambda_i + \lambda_j}, \quad (3)$$

where the $\lambda_i$’s are the eigenvalues and the $|i\rangle$’s, the eigenvectors of $\rho$.

A. Three-Dimensional Case

In [14], using the familiar Bloch sphere (unit ball in Euclidean 3-space) representation of the two-level quantum systems ($2 \times 2$ density matrices),

$$\rho = \frac{1}{2} \begin{pmatrix} 1 + z & x - iy \\ x + iy & 1 - z \end{pmatrix}, \quad r^2 = x^2 + y^2 + z^2 \leq 1, \quad (4)$$

it was found (cf. [2, p. 128]), here converting from cartesian to spherical coordinates,

$$x = r \cos \theta_1, \quad y = r \sin \theta_1 \cos \theta_2, \quad z = r \sin \theta_1 \sin \theta_2, \quad (5)$$

that

$$d_B(\rho, \rho + d\rho)^2 = \frac{1}{4} \left( \frac{1}{1 - r^2} dr^2 + dn^2 \right). \quad (6)$$
The term $dr^2$ corresponds to the radial component of the metric and $dn^2$, the tangential component ($dn^2 = r^2d\theta_1^2 + r^2\sin^2\theta_2$). In the setting of the quantum monotone metrics — the Bures metric serving as the minimal monotone one — it is appropriate to express the tangential component of the Bures metric (6) in the form \[8, eq. (3.17)],

$$
(1 + r)f_B(\frac{1-r}{1+r})^{-1},
$$

(7)

where $f_B(t) = \frac{1+t}{2}$ is an operator monotone function \[15\].

The volume element of the Bures metric (7) is $r^2\sin\theta_1(1-r^2)^2$, which can be normalized to a prior probability distribution over the Bloch sphere,

$$p_B = \frac{r^2\sin\theta_1}{\pi^2(1-r^2)}.
$$

(8)

B. Four-Dimensional Case

Now, we can construct a four-dimensional family of (properly normalized/unit trace) $2 \times 2$ escort density matrices (cf. \[16\]),

$$
\rho\{q\} = \left((1-r)^q + (1+r)^q\right)^{-1}\left(\begin{array}{cc}
1+z & x-iy \\
x+iy & 1-z
\end{array}\right)^q,
$$

(9)

for which $q = 1$ recovers the standard Bloch sphere representation \[4\]. Applying Hübner’s formula \[3\], we have found that the extended Bures metric (now incorporating the $q$-parameter) has the form

$$
d_{\text{Bures}_q}(\rho, \rho + d\rho)^2 = \frac{1}{4(1+Wr)^2}\left(W^q\log^2Wdq^2 + \frac{4qW^q\log W}{r^2-1}dqdr + \frac{q^2W^q}{(r^2-1)^2}dr^2 + \frac{(-1 + W^q)^2}{r^2}dn^2\right),
$$

(10)

where $W = \frac{1-r}{1+r}$, that is, the ratio of the two eigenvalues of $\rho$.

The tangential component of the metric \[11\] can be expressed as $(1 + r)f_{\text{Bures}_q}(W))^{-1}$, where

$$f_{\text{Bures}_q}(t) = \frac{2(1+t)(1+t^q)^2}{(-1 + t^q)^2}.
$$

(11)

This bivariate function appears (Fig. 2) to be monotonically-increasing for any fixed $q$ (cf. \[8\]).
FIG. 2: The function $f_{\text{Bures}}(t)$ that yields the tangential component (11) of the extended (four-dimensional) Bures metric (10).

Now, in the earlier stage of our analyses, due to a programming oversight, we were under the impression that the off-diagonal $dqdr$ term of (10) was simply zero. If we do employ the fully correct form, with this $dqdr$ term included, we find that the volume element is null. This, of course, could not yield a meaningful prior probability distribution. However, having proceeded under the impression that the $dqdr$ term was null, we obtained a number of results that appear to be of interest and of some relevance. Therefore, for much of this study, we will treat the $dqdr$ term as null, and thus deal with a truncated $q$-extended Bures metric.

In the context of the harmonic oscillators states, Pennini and Plastino have argued that, in addition to the physical lower bound (ignorance-amount) of $q \geq 0$ that in a quantal regime, $q$ can be no less than 1 — due to the Lieb bound on the Wehrl entropy. However, for the two-level quantum systems to the study of which we restrict ourselves here, the lower bound on the Wehrl entropy is $1/2$ [19, eq. (12)]. We, thus, consider $q \in [1/2, \infty)$ to be the range of possible values of the escort parameter $q$. In practice, though, we will, for numerical and graphical purposes and normalization of the (divergent over $q \in [1/2, \infty]$) truncated extended Bures volume element (Sec. V), consider that $q \in [1/2, 500]$.

In Fig. 3 we show the two-dimensional marginal volume element of (10) (after omission of the $dqdr$ term) — integrating out the spherical angles, $\theta_1, \theta_2$, and leaving the radial coordinate $r$ and the escort parameter $q$. In Fig. 4 further integrating out $r$, we show the
FIG. 3: Two-dimensional marginal of the *truncated* four-dimensional extended Bures volume element (10).

FIG. 4: One-dimensional marginal (12) over $q$ of the four-dimensional truncated extended Bures volume element (10), corresponding one-dimensional marginal volume element of (10) (after omission of the $dqdr$ term) over $q$. This (Fig. 4) has the exact expression

$$\frac{\pi(1 + \log 4)}{24q}.$$  

(12)

This prior, thus, conforms to Jeffreys’ rule — as opposed to the Bayes-Laplace rule, which would give a *constant* prior [20].

In Fig. 5, we integrate out $q \in [\frac{1}{2}, 500]$, leaving a (deep bowl-shaped) one-dimensional marginal over $r \in [0, 1]$. (The corresponding marginal in the unextended Bures case is \(\frac{\pi r^2}{2(1-r^2)}\), so it is simply increasing with $r$, in that case.) The associated indefinite integral...
FIG. 5: One-dimensional marginal (obtained from (13)) over $r$ of the four-dimensional extended Bures volume element $\text{vol. elem.}$ after omission of the off-diagonal $dqdr$ term over $q$ is

$$
\pi \frac{(q W^q (3 + W^{2q}) \log(W) - (1 + W^q) \left(2 W^q + (1 + W^q)^2 \log(1 + W^q)\right))}{6 (-1 + r^2) (1 + W^q)^3 \log(W)}.
$$

(So, we obtain the function plotted in Fig. 5 by substituting $q = 500$ and $q = \frac{1}{2}$ into (13) and taking the difference.)

For $q = 1$, the extended Bures metric (10) reduces to

$$
ds_{Bures, q=1}(\rho, \rho + d\rho)^2 = \frac{1}{16} (1 - r^2) \log^2 W dq^2 - \frac{1}{4} \log W dqdr + ds_B(\rho, \rho + d\rho)^2.
$$

Normalizing the volume element of this metric — but first nullifying the off-diagonal $dqdr$ term — to a (non-null) prior probability distribution over the Bloch sphere, we obtain (cf. (8)),

$$
p_{B_{q=1\text{trunc}}} = \frac{3 r^2 \sin \theta_1 \log \frac{1}{W}}{4 \pi (1 + \log 4)},
$$

one of the four priors that we rank (Fig. 1 and (1)) both by the comparative noninformativity test and Srednicki’s biasedness criterion.

C. Comparative Noninformativities in the Bures Setting

The relative entropy (Kullback-Leibler distance/information gain [21, 22]) of $p_B$ with respect to $p_{B_{q=1\text{trunc}}}$ [which we denote $S_{KL}(p_B, p_{B_{q=1\text{trunc}}})$] — that is, the expected value with respect to $p_B$ of $\log p_B$ — is 0.101846 “nats” of information. Now, reversing arguments, $S_{KL}(p_{B_{q=1\text{trunc}}}, p_B) = 0.0661775$. (We use the natural logarithm, and not 2 as a base, with
one nat equalling 0.531 bits.) Let us convert — using Bayes’ rule — these two (prior) probability distributions to posterior probability distributions ($post_B$ and $post_{Bures_q=1}$), by assuming three pairs of spin measurements, one each in the x-, y- and z-direction, each pair yielding one “up” and one “down”. This gives us the likelihood function (cf. [3, eq. (9)] [23, eq. (4.2)]),

$$L(x, y, z) = \frac{(1 - x^2)(1 - y^2)(1 - z^2)}{64}$$

(16)

(which we convert to the spherical coordinates in which we perform our Mathematica computations).

Then, we have $S_{KL}(post_B||p_{B_q=1\text{trunc}}) = 0.169782$ and $S_{KL}(post_{Bures_q=1}||p_B) = 0.197657$. The relative magnitudes of the information gains obtained by passing from priors to posteriors (0.101846 to 0.169782 and 0.0661775 to 0.197657) seems to suggest that $p_B$ is somewhat more noninformative than $p_{B_q=1\text{trunc}}$. This is confirmed, using the testing structure given in (3), (6) (cf. [3]), if we formally use a likelihood ($L(x, y, z)^{\frac{1}{2}}$), which is the square root of (16), to compute $post_B$ and $post_{Bures_q=1}$. Then, we see a decrease in relative entropy from 0.101846 to 0.093849 and an increase from 0.0661775 to 0.114669. So, $p_B$ can be made closer to $p_{B_q=1\text{trunc}}$ by adding information to it, but not vice versa, leading us to conclude that $p_B$ is more noninformative than $p_{B_q=1\text{trunc}}$, since it assumes less about the data. (Let us note, however, that in the class of monotone metrics [8], the Bures or minimal monotone metric appears to be the least noninformative (cf. [2, sec. 5]). The maximal monotone metric, on the other hand, is not normalizable to a proper prior probability distribution over the Bloch sphere [3]. So, there is an interesting question of whether there exists a single, distinguished normalizable monotone metric which is maximally noninformative.)

### III. FISHER INFORMATION METRIC OF HUSIMI DISTRIBUTIONS

Let us now move to a classical context, employing the (generalized) Husimi distributions [24], rather than density matrices to represent the two-level quantum systems. Use of the Fisher information (monotone) metric [25, 26] is now indicated. To generate the (properly normalized) escort Husimi distributions ($H_{\{q\}}$) (cf. [17]), from the Husimi distribution ($H = H_{\{1\}}$), we employ the formula (cf. [9]),

$$H_{\{q\}} = 2 (r + q r) \left( - (1 - r)^{1+q} + (1 + r)^{1+q} \right)^{-1} H^q.$$  

(17)
The tangential components of the Fisher information metric for the escort Husimi distributions \( H_q \) are of the form
\[
(1 + r) f_{F_q}(t) \] \(^{-1} \), where \([6, \text{eq. (29)}]\)
\[
f_{F_q}(t) = \frac{(-1 + q)(-1 + t)^2(-1 + t^{1+q})}{q(1 + t)(1 - q + t + qt - t^q - q t^q - t^{1+q} + q t^{1+q})}. \tag{18}
\]

In \([6, \text{sec. V.D}]\), we succeeded in finding similarly general (for all \( q \)) formulas for the denominators, but not the numerators, of the radial components.

In Fig. 6 we show (having to resort to some numerical integrations, since we lack explicit \([q\text{-general}]\) expressions for certain of the metric elements) the counterpart to Fig. 3 for the four-dimensional extended Husimi metric. Continuing with our numerical methods, we obtain the interesting unimodal curve (Fig. 7) — the peak being near \( q = 3.59782 \), with a value there of 0.448488. This portrays the one-dimensional marginal Husimi volume element over \( q \) (cf. Fig. 4). In Fig. 8 we show the (quite difficult-to-compute) one-dimensional marginal over \( r \) (cf. Fig. 5). (It appears the upturn near \( r = 1 \) may be simply a numerical artifact. The difficulty consists in that, in some sense, we have to repeatedly perform numerical integrations using results of other numerical integrations. It would be of interest to see how the curve changes as the range of \( q \in [\frac{1}{2}, 500] \) is modified.)
FIG. 7: One-dimensional marginal over $q$ of the four-dimensional extended Husimi volume element \cite{21}. There is a peak near $q = 3.59782$

FIG. 8: One-dimensional marginal over $r$ of the four-dimensional extended Husimi volume element \cite{21}. The upturn near $r = 1$ may be due to (hard-to-avoid) numerical inaccuracy.

**A. Three-dimensional metric**

For the case $q = 1$, the (unextended) three-dimensional Fisher information metric over the family of Husimi distributions takes the form \cite{6, eq. (2)]

$$
\begin{align*}
\, \text{vol. elem} \\
\begin{array}{c}
0.4 \\
0.3 \\
0.2 \\
0.1 \\
0.0 \\
\end{array}
\end{align*}
$$

$$
\begin{align*}
\begin{array}{c}
100 \\
200 \\
300 \\
400 \\
500 \\
\end{array}
\end{align*}
$$

\begin{align*}
\frac{ds_F}{ds_F(\rho, \rho + d\rho)^2} &= \frac{-2r - \log(\frac{1-r}{1+r})}{2r^3} dr^2 + \left((1 + r) f_F(\frac{1-r}{1+r})\right)^{-1} dn^2. \\
\end{align*}

\text{(19)}

Here,

$$
\begin{align*}
f_F(t) &= \frac{(t-1)^3}{t^2 - 2t \log t - 1}, \\
\end{align*}

\text{(20)}$$

which is the limiting case ($q \to 1$) of \cite{11}. To normalize the volume element of this metric \cite{19} to a prior probability distribution ($p_F$), we divide it by 1.39350989 \cite{6}. 

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B. Four-dimensional metric

In the extended (four-dimensional) case (cf. (14)), after having set \( q = 1 \), we have,

\[
\begin{align*}
    ds_{F_q=1}(\rho, \rho + d\rho)^2 &= \left( \frac{1}{4} - \frac{(-1 + r^2)^2 \log^2 W}{16^2} \right) dq^2 \\
    &\quad + \frac{2r - (-1 + r^2) \log W}{2r^2} dq dr + ds_F(\rho, \rho + d\rho)^2.
\end{align*}
\]

(21)

(So, the metric tensor here, in the same manner as in the untruncated extended Bures case (10), is not fully diagonal. We do not truncate the \( q \)-extended Fisher information metric (21) in any of our analyses.) To normalize its (non-null) volume element to a prior probability distribution \( (p_{F_q=1}) \) over the Bloch sphere, we must divide by 0.24559293.

IV. COMPARATIVE NONINFORMATIVITY ANALYSIS

We have that \( S_{KL}(p_F||p_{F_q=1}) = 0.229666 \) and \( S_{KL}(p_{F_q=1}||p_F) = 0.170145 \). Further, using the likelihood (16), based on six hypothetical measurements to generate posteriors, we obtain \( S_{KL}(post_F, p_{F_q=1}) = 0.70766 \) and \( S_{KL}(post_{F_q=1}||p_F) = 0.061738 \). So, the comparative noninformativity test, which was initially developed by Clarke [4], leads us to a firm conclusion that the four-dimensional-based probability distribution \( p_{F_q=1} \) is more noninformative in nature than the three-dimensional-based \( p_F \).

Additionally, \( S_{KL}(p_B||p_{F_q=1}) = 0.148269 \) and \( S_{KL}(p_{F_q=1}||p_B) = 0.0989669 \). These are converted, respectively, to 0.283218 and 0.0842879 if we replace the first arguments of the two relative entropy functionals by posterior distributions based on the (formal) square root \( (L(x, y, z)^{\frac{1}{2}}) \) of the likelihood function (16). Thus, we can conclude that \( p_{F_q=1} \) is also more noninformative than \( p_B \).

Further, \( S_{KL}(p_{B_{q=1, trunc}}||p_{F_q=1}) = 0.105463 \) and \( S_{KL}(p_{F_q=1}||p_{B_{q=1, trunc}}) = 0.0914175 \). Again, using the formal square root \( (L(x, y, z)^{\frac{1}{2}}) \) of the likelihood, we obtain changes, respectively, to 0.245602 and 0.0408236. So, our conclusion here is that \( p_{F_q=1} \) is also more noninformative than \( p_{B_{q=1, trunc}} \). We already know from [6] that \( p_B \) is considerably more noninformative than \( p_F \).

Continuing along these lines, \( S_{KL}(p_{B_{q=1, trunc}}||p_F) = 0.0191948 \) and \( S_{KL}(p_F||p_{B_{q=1, trunc}}) = 0.0234599 \) (so the two distributions are relatively close to one another). Using \( (L(x, y, z)^{\frac{1}{2}}) \) to
generate posterior distributions, the first statistic is altered (slightly decreased) to 0.0143147, while the second statistic jumps to 0.1047772.

So, assembling these several relative entropy statistics, we have the previously indicated ordering of the four priors (1). (The conclusions of the comparative noninformativity test appear to be transitive in nature, although I can cite no explicit theorem to that effect.)

**A. Relation to Srednicki’s Criterion for Priors**

In Fig. 1 we show the one-dimensional marginal probabilities of the four prior probabilities over the radial coordinate $r$ in the near-to-pure-state range $r \in [.995, 1]$. The dominance ordering in this plot fully complies with that (1) found by the information-theoretic-based comparative noninformativity test. (We note that this ordering is not simply reversed near to the fully mixed state $[r = 0]$.) Conjecturally, this could be seen as a specific case of some (yet unproven) theorem — perhaps utilizing the convexity and decreasing-under-positive-mappings properties [27, p. 35] of the relative entropy functional.

So, the information-theoretic (comparative-noninformativity) test appears to incorporate Srednicki’s criterion of “biasedness to pure states” [3]. (Of course, it would be interesting to test the consistency between the comparative noninformativity test and Srednicki’s criterion with a larger number of priors, as well as in higher-dimensional quantum settings (cf. [28]).) Srednicki does not explicitly observe that increasing biasedness to pure states corresponds to increasing noninformativity. He asserts that “we must decide how biased we are towards pure states”.

Srednicki focused on two possible priors. One was the uniform distribution over the Bloch sphere (unit ball). In [5, sec. 2.2], we had concluded that this distribution was less noninformative than $p_B$, in full agreement with contemporaneous work of Hall [2]. The second prior (“the Feynman measure”), which Srednicki points out is less biased to the pure states than the uniform distribution, was discussed in [29]. Neither of the two priors analyzed by Srednicki corresponds to the normalized volume element of a monotone metric [5, 29].
V. \textit{q}-EXTENDED INFERENCE

In the setting of the \textit{q}-parameterized escort density matrices (9), the factor $\frac{1-z^2}{4}$ in the likelihood (16), giving the probability (in the standard three-dimensional Bloch sphere setting) of one spin-up and one spin-down being measured in the \textit{z}-direction, would be replaced by

$$L_q(z) = \frac{r^2(1 + W^q)^2 - (-1 + W^q)^2 z^2}{4r^2(1 + W^q)^2},$$

(22)

and similarly for the \textit{x}- and \textit{y}-directions. (For $q = 1$, we recover $\frac{1-z^2}{4}$.)

It would be interesting to ascertain if the volume elements of the extended four-dimensional (truncated) Bures and Husimi metrics (10 and 21) could be integrated over the product of the Bloch sphere and $q \in [\frac{1}{2}, \infty]$ and normalized to (prior) probability distributions. Then, using likelihoods incorporating the form (22), one could conduct the comparative noninformativity test in a \textit{four}-dimensional setting, rather than only the \textit{three}-dimensional one employed throughout this study. It turns out, however, that the three-fold integral — holding \textit{q} fixed — of the truncated volume element of (11) over the Bloch sphere is given by our formula (12). Therefore, the four-fold integral of the one-dimensional marginal over the indicated product region with $q \in [\frac{1}{2}, \infty]$ must diverge. So, to achieve a proper probability distribution one would have to truncate \textit{q} above a certain value.

Continuing along these lines, we omitted \textit{q} above 500 (and below $q = \frac{1}{2}$) and normalized the volume element of the (truncated) extended Bures metric to a proper probability distribution. Then, the information gain with respect to such a prior, using $L_q(z)$, is 0.0597923 nats of information, while a single up or down measurement yields 0.134651 nats, and two measurements along the same axis giving the same outcome leads to an information gain of 0.349601. The analogous three (slightly larger) statistics, working in the unextended framework (where \textit{q} does not explicitly enter, and is implicitly understood to equal 1), using $p_B$ as prior, are, respectively, $\frac{7}{6} - \log 3 \approx 0.0680544$, and

$$\frac{8p_{F_q}(\{\frac{1}{2}, 1, 2\}, \{\frac{3}{2}, \frac{5}{2}\}, 1) - \pi (-5 + \log(64)) - 6 - 12K}{6\pi} \approx 0.140186,$$

(23)

(where $p_{F_q}$ denotes a generalized hypergeometric function and $K \approx 0.915965594177$ is Catalan’s constant) and $\frac{59}{30} - \log 5 \approx 0.357229$. (We encountered numerical difficulties using Mathematica in attempting to extend these analyses to measurements conducted in more than one direction, unless we restricted \textit{q} to a range no larger than on the order of 10.)
One might also consider the possible relevance of \(q\)-analogs of the Clarke comparative noninformativity test, using \(q\)-relative entropy (Kullback-Leibler) divergence \[30, 31\].

VI. FOUR-DIMENSIONAL \(3 \times 3\) DENSITY MATRICES

In \[28\], we considered an extension of the \(2 \times 2\) density matrices \[4\] to the \(3 \times 3\) form (by incorporating an additional parameter \(v\))

\[
\rho = \frac{1}{2} \begin{pmatrix} v + z & 0 & x - iy \\ 0 & 2 - 2v & 0 \\ x + iy & 0 & v - z \end{pmatrix}, \quad r^2 = x^2 + y^2 + z^2 \leq v^2; \quad 0 \leq v \leq 1, \quad (24)
\]

The Bures metric was found there to take the form

\[
d_{B_n=3}(\rho, \rho + d\rho)^2 = \frac{1}{4} \left( \frac{r^2 - v}{1 - v(r^2 - v^2)} dv^2 + \frac{r}{r^2 - v^2} dvdr + \frac{v}{v^2 - r^2} dr^2 + \frac{1}{v} dn^2 \right). \quad (25)
\]

(So, the tangential component is independent of \(r\), as with \[6\] (cf. \[2\]).) Normalizing the volume element of \[25\], we obtain the prior probability distribution \[28\, \text{eq. (18)}\]

\[
p_{B_n=3} = \frac{3r^2 \sin \theta_1}{4\pi^2 v \sqrt{1 - v \sqrt{v^2 - r^2}}}. \quad (26)
\]

We have calculated that the (five-dimensional) \(q\)-extension of this metric has a tangential component of the form

\[
\frac{((-r + v)^q - (r + v)^q)^2}{4r^2 ((-r + v)^q + (r + v)^q) ((2 - 2v)^q + (-r + v)^q + (r + v)^q)}, \quad (27)
\]

but have not yet been able to derive simple forms for the other entries of this metric tensor.

Numerical tests appear to indicate that the volume element of this \(q\)-extended Bures metric tensor is (also) identically zero.

VII. \(q\)-EXTENSION OF THE BURES METRIC FOR THE ABE-RAJAGOPAL STATES

Since our two attempts above to extend the Bures metric from an \(n\)-dimensional setting to an \((n + 1)\)-dimensional framework, by embedding the \(q\) order parameter, have yielded metrics (one of them being \[10\]) with zero volume elements, we were curious as to whether
or not we could obtain, in some other quantum context, a nondegenerate $q$-extension of the Bures metric. In this regard, we turned our attention to the paper, “Quantum entanglement inferred by the principle of maximum nonadditive entropy” of Abe and Rajagopal [32] (cf. [33, eq. (14)]).

Their principal object of study is a $4 \times 4$ density matrix [32, eq. (32)], being ostensibly parameterized by three variables, the order (nonadditivity) parameter $q$, the $q$-expected value $b_q$ of the Bell-CHSH observable and its dispersion $\sigma_q^2$. (Two of the four eigenvalues of the density matrix are always equal. In [34], it was asserted that for the cases $q = \frac{1}{2}$ and $1$, the associated separability probabilities were equal to the “silver mean”, that is, $\sqrt{2} - 1 \approx 0.414214$ (cf. [35, 36]). We have confirmed these two probabilities here — at least in a numerical sense — and also found that the Bures volume of separable and nonseparable states is approximately 0.785398 [which we believe is an approximation to $\frac{\sqrt{2}}{4} \approx 0.7853981634$] for both $q = \frac{1}{2}$ and $1$ [as well as for $q = \frac{1}{4}$ and $\frac{1}{3}$]. It appears very computationally challenging to compute separability probabilities for values of $q$ other than $\frac{1}{2}$ and $1$, although it is an intriguing hypothesis that they are equal to $\sqrt{2} - 1$ for all (positive) $q$.

We applied the Hübner formula [33] for the Bures metric to this family of $4 \times 4$ density matrices, considering $q$ as a freely-varying parameter, along with $b_q$ and $\sigma_q^2$. Computing the $3 \times 3$ Bures metric tensor, and then setting $q = 1$, we obtain the metric

$$ds_{AbeRaj_{q=1}}(\rho, \rho + d\rho)^2 = \frac{c}{1024}dq^2 + \log(-2\sqrt{2}b_q + \sigma_q^2) - \log(2\sqrt{2}b_q + \sigma_q^2)\,dqdb_q + \frac{2\log(8 - \sigma_q^2) - \log(-2\sqrt{2}b_q + \sigma_q^2) - \log(2\sqrt{2}b_q + \sigma_q^2)}{32}\,dqd\sigma_q^2 + \frac{\sigma_q^2}{-32b_q^2 + 4(\sigma_q^2)^2}(db_q)^2 + \frac{b_q}{16b_q^2 - 2(\sigma_q^2)^2}db_qd\sigma_q^2 + \frac{b_q^2 - \sigma_q^2}{4(-8 + \sigma_q^2)(-8b_q^2 + (\sigma_q^2)^2)}(d\sigma_q^2)^2.$$  

Here, we have

$$c = -4\log(8 - \sigma_q^2)^2\sigma_q^2(-8 + \sigma_q^2) + 2\log(-2\sqrt{2}b_q + \sigma_q^2)\log(2\sqrt{2}b_q + \sigma_q^2)(8b_q^2 - \sigma_q^4) + \log(-2\sqrt{2}b_q + \sigma_q^2)^2(8b_q^2 + \sigma_q^2)(-16 + \sigma_q^2) - 4\sqrt{2}b_q(-8 + \sigma_q^2)$$  

$$-\log(2\sqrt{2}b_q + \sigma_q^2)^2(8b_q^2 + \sigma_q^2)(-16 + \sigma_q^2) + 4\sqrt{2}b_q(-8 + \sigma_q^2) + 4\log(8 - \sigma_q^2)(-8 + \sigma_q^2)\log(-2\sqrt{2}b_q + \sigma_q^2)(-2\sqrt{2}b_q + \sigma_q^2) + \log(2\sqrt{2}b_q + \sigma_q^2)(2\sqrt{2}b_q + \sigma_q^2).$$
Numerical computations indicate that the volume element of the metric $ds_{AbeRaj_q}(\rho, \rho + d\rho)^2$, for any value of $q$, is zero. So, we have, to this point in our analyses, yet to find a nondegenerate $q$-extension of the Bures metric (if one is so possible). (We investigated the possibility of analyzing the $4 \times 4$ density matrix in [33, eq. (14)], but it appears to have one zero eigenvalue, thus rendering the Hübner formula (3) inapplicable (cf. [37, sec. 3.4]).)

In the unextended (two-parameter) case, the nondegenerate volume element (with $q = 1$) is

$$V_{AbeRaj_q=1} = \sqrt{-\frac{1}{(-8+\sigma_q)(-8b_2^2+(\sigma_q)^2)}} \cdot 4. \quad (30)$$

VIII. CONCLUDING REMARKS

Naudts [16] introduced the concept of a $\phi$-exponential family of density operators $\rho_\theta$ (for which the obvious example is $\phi(u) = u^q$). He showed that the $\phi$-exponential family of density operators, together with a family of escort density operators, optimizes a generalized version of the well-known Cramér-Rao lower bound. He assumes that certain Hamiltonians are two-by-two commuting. Therefore, the quantum information manifold $(\rho_\theta)_\theta$ is abelian, which “is clearly too restrictive for a fully quantum-mechanical theory”. He suggests further work to remove this restriction.

Abe regarded the order of the escort distribution $q$ as a parameter [38]. He studied the geometric structure of the one-parameter family of escort distributions using the Kullback divergence, and showed that the Fisher metric is given in terms of the generalized bit variance, which measures fluctuations of the crowding index of a multifractal.

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