SYMMETRIC q-GAMMA FUNCTION.

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Abstract

In this work we are interested by giving new characterizations of the symmetric q-Gamma function and show that there are intimately related.

Key Words: q-analogue, gamma function, characterization.

1 Introduction

In literature the characterizations of the well known Gamma function are studied by many authors [[2],[4],[12]]. As same as the Gamma function, the characterization of the q-Gamma function was studied by Elmonser, Brahim and Fitouhi in [5], they proved the following results:

Theorem 1 *The q-Gamma function is the unique function $f(x) > 0$ on $]0, +\infty[$ that satisfies the following properties:*
a) $f(1) = 1$
b)$f(x+1) = [x]_q f(x)$
c)$f(x+n) = (1-q)^{[x]_q - x} f(n)[n]_q^{[x]_q} t_n(x)$*, where* $t_n(x) \to 1$ *as* $n \to \infty$*.*

The second theorem gives the relationship between three different characterizations of the q-Gamma function:

Theorem 2 *For a q-PG function f, the following properties are equivalent:*
(C) $\ln f$ *is convex on* $]0, +\infty[$*,*
(L)$L(n+x) = ([x]_q - x)\ln(1-q) + L(n) + x\ln(n+1) + r_n(x)$*,*
where $L(x) = \ln f(x+1)$ *and* $r_n(x) \to 0$ *as* $n \to \infty$*,*
(P) $f(x+n) = (1-q)^{[x]_q - x} f(n)[n]_q^{[x]_q} t_n(x)$*,*
where $t_n(x) \to 1$ *as* $n \to \infty$*.*
A q-PG function f satisfying these properties is equal to $c\Gamma_q(x)$, for some constant c.

where the a q-PG function (pre-q-gamma function) is a positive function f on $]0, +\infty[$ satisfying the functional equation $f(x+1) = [x]_q f(x)$.

In the present paper we give characterizations of the symmetric q-Gamma function, introduced by K. Brahim and Yosr Sidomou in [3], and we show that there are intimately related.

2 Notations and Preliminaries

We recall some usual notions and notations used in the q-theory (see [6] and [8]). Throughout this paper, we assume $q \in]0,1[$.

For $a \in \mathbb{C}$, the q-shifted factorials are defined by

$$(a;q)_0 = 1, \qquad (a;q)_n = \prod_{i=0}^{n-1}(1-aq^i) = (1-a)(1-aq)....(1-aq^{n-1}), \qquad n = 1,2,..... \tag{1}$$

$$(a;q)_\infty = \prod_{i=0}^{\infty}(1-aq^i). \tag{2}$$

We also denote

$$[x]_q = \frac{1-q^x}{1-q}, \quad x \in \mathbb{C}, \tag{3}$$

$$\widetilde{[x]}_q = \frac{q^x - q^{-x}}{q-q^{-1}} =, \quad x \in \mathbb{C}, \tag{4}$$

$$[n]_q! = \prod_{k=1}^{n}[k]_q = \frac{(q;q)_n}{(1-q)^n}, \quad n \in \mathbb{N}. \tag{5}$$

and

$$\widetilde{[n]}_q! = \prod_{k=1}^{n}\widetilde{[k]}_q, \quad n \in \mathbb{N}. \tag{6}$$

One can see that

$$\widetilde{[x]}_q = q^{-(x-1)}[x]_{q^2}. \tag{7}$$

3 The symmetric q-Gamma function:

The q-Gamma function $\Gamma_q(x)$, a q-analogue of Euler's gamma function, was introduced by Thomae [11] and later by Jackson [7] as the infinite product:

$$\Gamma_q(x) = \frac{(q;q)_\infty(1-q)^{1-x}}{(q^x;q)_\infty} \quad ,x>0, \tag{8}$$

where q is a fixed real number $0 < q < 1$.

Recently, K. Brahim and Yosr Sidomou [3] introduced the symmetric q-Gamma function as follows:

$$\widetilde{\Gamma}_q(z) = q^{-\frac{(z-1)(z-2)}{2}}\Gamma_{q^2}(z), \quad ,z>0, q>0, q \neq 1, \tag{9}$$

where

$$\Gamma_q(z) = \begin{cases} \dfrac{(q,q)\infty}{(q^x,q)\infty}(1-q)^{1-x}, & \text{if } \ 0<q<1, \\ \dfrac{(q^{-1},q^{-1})\infty}{(q^{-x},q^{-1})\infty}(1-q)^{1-x}q^{\frac{x(x-1)}{2}}, & \text{if } \ q>1. \end{cases} \tag{10}$$

They proved that it is symmetric under the interchange $q \leftrightarrow q^{-1}$ and satisfies a q-analogue of the Bohr-Mollerup theorem for $q \neq 1$:

Theorem 3 *Let $q>0$, $q\neq 1$. The only function $f \in C^2((0,\infty))$ satisfying the conditions:*
(a) $f(1)=1$.
(b) $f(x+1) = \widetilde{[x]}_q f(x)$.
(c) $\dfrac{d^2}{dx^2} Log f(x) \geq |Log q|$ for positive x,
is the symmetric q-Gamma function.

Using the relation (9) and the properties of the q-Gamma function [[5], [10]] we derive the following theorem:

Theorem 4

$$\widetilde{\Gamma}_q(x) = \lim_{n\to+\infty} q^{-\frac{(x-1)(x-2)}{2}}(1-q^2)^{[x]_{q^2}-x} \frac{[n]_{q^2}^{[x]_{q^2}}[n]_{q^2}!}{[x]_{q^2}[x+1]_{q^2}...[x+n]_{q^2}}, \quad x>0. \tag{11}$$

4 Characterization of the q-Gamma function:

As it is proved in [[3], [5]], we establish new characterizations of the symmetric q-Gamma function. The first characterization is given by the following theorem:

Theorem 5 *There exists a unique function $f(x)>0$ on $]0,+\infty[$ that satisfies the following properties:*
a) $f(1)=1$
b)$f(x+1) = \widetilde{[x]}_q f(x)$
c)$f(x+n) = q^{-\frac{x^2+2nx-3x}{2}}(1-q^2)^{[x]_{q^2}-x}[n]_{q^2}^{[x]_{q^2}} f(n)t_n(x)$, where $t_n(x)\to 1$ as $n\to\infty$.

Proof. .
First we prove that $\widetilde{\Gamma}_q(x)$ satisfies conditions (a), (b) and (c).
From Theorem 3, the symmetric q-Gamma function satisfies the condition (a) $\widetilde{\Gamma}_q(1)=1$, and the condition (b) $\widetilde{\Gamma}_q(x+1) = \widetilde{[x]}_q \widetilde{\Gamma}_q(x)$.

As a consequence of the two properties, we get $\widetilde{\Gamma}_q(n) = \widetilde{[n-1]}_q!$

(c) Let $s_n(x) = \dfrac{\widetilde{\Gamma}_q(x)}{q^{-\frac{(x-1)(x-2)}{2}}(1-q^2)^{[x]_{q^2}-x}\widetilde{\Gamma}_{n,q}(x)}$,

where $\widetilde{\Gamma}_{n,q}(x) = \dfrac{[n]_{q^2}^{[x]_{q^2}}[n]_{q^2}!}{[x]_{q^2}[x+1]_{q^2}...[x+n]_{q^2}} = \dfrac{[n]_{q^2}^{[x]_{q^2}}\widetilde{[n]}_q!}{q^{nx+x-1}\widetilde{[x]}_q\widetilde{[x+1]}_q...\widetilde{[x+n]}_q}$,

then $\widetilde{\Gamma}_q(x) = s_n(x)q^{-\frac{(x-1)(x-2)}{2}}(1-q^2)^{[x]_{q^2}-x}\widetilde{\Gamma}_{n,q}(x)$ and $\lim\limits_{n\to+\infty} s_n(x) = 1$.
For $n\in\mathbb{N}$ and $x>0$, we apply (b) n times to get

$$\begin{aligned}
\widetilde{\Gamma}_q(x+n) &= \widetilde{[x+n-1]}_q ... \widetilde{[x+1]}_q \widetilde{[x]}_q \widetilde{\Gamma}_q(x) \\
&= \frac{\widetilde{[x+n]}_q ... \widetilde{[x+1]}_q \widetilde{[x]}_q}{\widetilde{[x+n]}_q} . q^{-\frac{(x-1)(x-2)}{2}} (1-q^2)^{[x]_{q^2}-x} \frac{[n]_{q^2}^{[x]_{q^2}} \widetilde{[n]}_q !}{q^{nx+x-1} \widetilde{[x]}_q \widetilde{[x+1]}_q ... \widetilde{[x+n]}_q} . s_n(x) \\
&= q^{-\frac{x^2+2nx-3x}{2}} (1-q^2)^{[x]_{q^2}-x} [n]_{q^2}^{[x]_{q^2}} \widetilde{\Gamma}_q(n) t_n(x).
\end{aligned}$$

Where $t_n(x) = q^{-x} \dfrac{\widetilde{[n]}_q}{\widetilde{[x+n]}_q} . s_n(x)$. Thus, $\widetilde{\Gamma}_q(x+n) = q^{-\frac{x^2+2nx-3x}{2}} (1-q^2)^{[x]_{q^2}-x} [n]_{q^2}^{[x]_{q^2}} \widetilde{\Gamma}_q(n) t_n(x)$ and $t_n(x) \to 1$ as $n \to +\infty$.

To show uniqueness, we assume $f(x)$ is a function that satisfies (a), (b) and (c). From properties (a) and (b), we have

$$f(n) = \widetilde{[n-1]}_q !. \tag{12}$$

$$f(x+n) = \widetilde{[x+n-1]}_q \widetilde{[x+n-2]}_q ... \widetilde{[x+1]}_q \widetilde{[x]}_q f(x). \tag{13}$$

Combining (12),(13) and (c) together, we have

$$\begin{aligned}
f(x) &= q^{-\frac{x^2+2nx-3x}{2}} (1-q^2)^{[x]_{q^2}-x} \frac{[n]_{q^2}^{[x]_{q^2}} \widetilde{[n-1]}_q !}{\widetilde{[x+n-1]}_q \widetilde{[x+n-2]}_q ... \widetilde{[x+1]}_q \widetilde{[x]}_q} t_n(x) \\
&= q^{-\frac{(x-1)(x-2)}{2}} (1-q^2)^{[x]_{q^2}-x} \widetilde{\Gamma}_{n,q}(x) . s_n(x),
\end{aligned}$$

where $s_n(x) = q^x \dfrac{\widetilde{[x+n]}_q}{\widetilde{[n]}_q} t_n(x) \to 1$ as $n \to +\infty$. Therefore $f(x) = \Gamma_q(x)$ and hence f is uniquely determined. This completes the proof.

5 Relationship between characterizations

In what follows, we will adopt the terminology of the following definition.

Definition 1 *A function f is said to be a qs-PG function (pre-symmetric-q-gamma function), if f is positive on $]0, +\infty[$ and satisfies the functional equation*
$f(x+1) = \widetilde{[x]}_q f(x)$.

In the previous section we showed that the property

$$f(x+n) = q^{-\frac{x^2+2nx-3x}{2}} (1-q^2)^{[x]_{q^2}-x} [n]_{q^2}^{[x]_{q^2}} f(n) t_n(x)$$

characterizes the q-gamma function. In this section we will give three properties which are equivalent to one another for a qs-PG function and characterize the symmetric q-gamma function.

Theorem 6 *For a q-PG function f, the following properties are equivalent:*
(C) $\ln f$ is convex on $]0, +\infty[$,
(L)$L(n+x) = -\dfrac{x^2+2nx-3x}{2} \ln q + ([x]_{q^2} - x) \ln(1-q^2) + L(n) + [x]_{q^2} \ln[n+1]_{q^2} + r_n(x)$,

where $L(x)=\ln f(x+1)$ *and* $r_n(x)\to 0$ *as* $n\to\infty$,
(P) $f(x+n)=q^{-\frac{x^2+2nx-3x}{2}}(1-q^2)^{[x]_{q^2}-x}[n]_{q^2}^{[x]_{q^2}}f(n)t_n(x)$,
where $t_n(x)\to 1$ *as* $n\to\infty$.
A qs-PG function f *satisfying these properties is equal to* $c\widetilde{\Gamma}_q(x)$,*for some constant* c.

Proof. .
(a) $(P)\Leftrightarrow(L)$. We have

$$\begin{aligned}
(P) \quad &\Leftrightarrow \quad f(x+(n+1))=q^{-\frac{x^2+2nx-3x}{2}}(1-q^2)^{[x]_{q^2}-x}f(n+1)[n+1]_{q^2}^{[x]_{q^2}}t_{n+1}(x),\\
&\qquad t_{n+1}(x)\to 1\\
&\Leftrightarrow \quad \ln f(x+(n+1))=-\frac{x^2+2nx-3x}{2}\ln q+([x]_{q^2}-x)\ln(1-q^2)+\ln f(n+1)\\
&\qquad +[x]_{q^2}\ln[n+1]_{q^2}+\ln t_{n+1}(x), t_{n+1}(x)\to 1\\
&\Leftrightarrow \quad L(x+n)=-\frac{x^2+2nx-3x}{2}\ln q+([x]_{q^2}-x)\ln(1-q^2)+L(n)\\
&\qquad +[x]_{q^2}\ln[n+1]_{q^2}+r_n(x), r_n(x)\to 0\\
&\Leftrightarrow \quad (L).
\end{aligned}$$

(b) $(C)\Longrightarrow(P)$. Let $m<x\le m+1$, where $m=0,1,2,...$ For any natural n, $n+m-1<n+m<n+x\le n+m+1$. The convexity of $\ln f$ gives us (we write $L_m=\ln f(n+m)$)

$$\frac{L_m-L_{m-1}}{n+m-(n+m-1)}\le\frac{\ln f(n+x)-\ln f(n+m)}{(n+x)-(n+m)}\le\frac{L_{m+1}-L_m}{(n+m+1)-(n+m)}$$

$$\Leftrightarrow (x-m)\ln\widetilde{[n+m-1]}_q\le\ln\frac{f(n+x)}{f(n+m)}\le(x-m)\ln\widetilde{[n+m]}_q$$

$$\Leftrightarrow \widetilde{[n+m-1]}_q^{\,x-m}\le\frac{f(n+x)}{\widetilde{[n+m-1]}_q\widetilde{[n+m-2]}_q...\widetilde{[n]}_qf(n)}\le\widetilde{[n+m]}_q^{\,x-m}$$

$$\Leftrightarrow \widetilde{[n+m-1]}_q^{\,x}T_m\le\frac{f(n+x)}{f(n)}\le\widetilde{[n+m]}_q^{\,x}T_m\frac{\widetilde{[n+m-1]}_q^{\,m}}{\widetilde{[n+m]}_q^{\,m}},$$

where $T_m=\dfrac{\widetilde{[n+m-1]}_q\widetilde{[n+m-2]}_q...\widetilde{[n]}_q}{\widetilde{[n+m-1]}_q^{\,m}}=q^{\frac{m(m-1)}{2}}\dfrac{[n+m-1]_{q^2}[n+m-2]_{q^2}...[n]_{q^2}}{[n+m-1]_{q^2}^m}$.
Therefore, we have

$$\lim_{n\to+\infty}q^{nx}\frac{f(n+x)}{f(n)}=\frac{q^{-\frac{x^2-3x}{2}}}{(1-q^2)^x},$$

by the squeezing theorem. If we let

$$t_n(x)=\frac{q^{\frac{x^2+2nx-3x}{2}}f(n+x)}{(1-q^2)^{[x]_{q^2}-x}f(n)[n]_{q^2}^{[x]_{q^2}}},$$

then

$$f(n+x)=q^{-\frac{x^2+2nx-3x}{2}}(1-q^2)^{[x]_{q^2}-x}f(n)[n]_{q^2}^{[x]_{q^2}}t_n(x),$$

where $t_n(x)\to 1$ as $n\to\infty$. This proves that f satisfies (P).
(c) $(P)\Longrightarrow(C)$. From the uniqueness part of the proof of the Theorem 5 we have

$f(x) = f(1) \lim_{n\to+\infty} q^{-\frac{(x-1)(x-2)}{2}}(1-q^2)^{[x]_{q^2}-x}\Gamma_{n,q}(x).$
Using the fact that the limit function of a convergent sequence of convex functions is convex, it suffices to show that $\ln\left(q^{-\frac{(x-1)(x-2)}{2}}(1-q^2)^{[x]_{q^2}-x}\Gamma_{n,q}(x)\right)$ is convex.
Now

$$\begin{aligned}\ln\left(q^{-\frac{(x-1)(x-2)}{2}}(1-q^2)^{[x]_{q^2}-x}\Gamma_{n,q}(x)\right) &= -\frac{(x-1)(x-2)}{2}\ln q + ([x]_{q^2}-x)\ln(1-q^2) \\ &\quad +[x]_{q^2}\ln[n]_{q^2} + \ln([n]_{q^2}!) - \ln[x]_{q^2} - ... - \ln[x+n]_{q^2}.\end{aligned}$$

Therefore, we have

$$\begin{aligned}\left(\ln\left(q^{-\frac{(x-1)(x-2)}{2}}(1-q^2)^{[x]_{q^2}-x}\Gamma_{n,q}(x)\right)\right)' &= (-x+\frac{3}{2})\ln q + \left(-2\frac{\ln q}{1-q^2}q^{2x}-1\right)\ln(1-q^2) \\ &\quad + \left(-2\frac{\ln q}{1-q^2}q^{2x}\ln[n]_{q^2}\right) + \frac{2\ln q}{1-q^2}\frac{q^{2x}}{[x]_{q^2}} + ... \\ &\quad + \frac{2\ln q}{1-q^2}\frac{q^{2(x+n)}}{[x+n]_{q^2}}.\end{aligned}$$

And so

$$\begin{aligned}\left(\ln\left(q^{-\frac{(x-1)(x-2)}{2}}(1-q^2)^{[x]_{q^2}-x}\Gamma_{n,q}(x)\right)\right)'' &= -\ln q - 4\frac{(\ln q)^2}{1-q^2}q^{2x}(\ln(1-q^2) + \ln\frac{1-q^{2n}}{1-q^2}) \\ &\quad +4\frac{(\ln q)^2}{1-q^2}[\frac{q^{2x}[x]_{q^2} + \frac{q^{4x}}{1-q^2}}{[x]^2_{q^2}} + ... \\ &\quad + \frac{q^{2(x+n)}[x+n]_{q^2} + \frac{q^{4(x+n)}}{1-q^2}}{[x+n]^2_{q^2}}] \\ &= -\ln q - 4\frac{(\ln q)^2}{1-q^2}q^{2x}(\ln(1-q^{2n})) \\ &\quad +4\frac{(\ln q)^2}{1-q^2}[\frac{q^{2x}[x]_{q^2} + \frac{q^{4x}}{1-q^2}}{[x]^2_{q^2}} + ... \\ &\quad + \frac{q^{2(x+n)}[x+n]_{q^2} + \frac{q^{4(x+n)}}{1-q^2}}{[x+n]^2_{q^2}}].\end{aligned}$$

Then
$\left(\ln\left((1-q)^{[x]_q-x}\Gamma_{n,q}(x)\right)\right)'' > 0.$
This completes the proof.

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