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Research Article

On Carlitz's Type Modified Degenerate q-Changhee Polynomials and Numbers

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Recently, Dolgy-Jang-Kwon-Kim introduced Carlitz's type q-Changhee polynomials. In this paper, we define Carlitz's type modified degenerate q-Changhee polynomials and investigate some interesting identities of these polynomials.

1. Introduction

Let p be a prime number with $p \equiv 1 (\mathrm{mod}\, 2)$. Throughout this paper, $\mathbb{Z}_p$, $\mathbb{Q}_p$, and $\mathbb{C}_p$ denote the ring of p-adic integers, the field of p-adic rational numbers, and the completion of the algebraic closure of $\mathbb{Q}_p$, respectively. The p-adic norm $|\cdot|_p$ is normalized as $|p|_p = 1/p$. Let q be an indeterminate in $\mathbb{C}_p$ such that $|1-q|_p < p^{-1/(p-1)}$. The q-analogue of number x is defined as $[x]_q = (q^x-1)/(q-1)$. As is well known, the Euler polynomials are defined by the generating function to be

$$\frac{2}{e^t+1}e^{xt} = \sum_{n=0}^{\infty} E_n(x)\frac{t^n}{n!} \tag{1}$$

(see [1–5]).

When $x = 0$, $E_n = E_n(0) (n \geq 0)$ are called the Euler numbers.

Recall that Carlitz considered the q-analogue of Euler numbers which are given by the recurrence relation as follows:

$$\mathscr{E}_{0,q} = 1,$$
$$q\left(q\mathscr{E}_q + 1\right)^n + \mathscr{E}_{n,q} = \begin{cases} [2]_q, & \text{if } n = 0, \\ 0, & \text{if } n \geq 1 \end{cases} \tag{2}$$

with the usual convention about replacing $\mathscr{E}_q^n$ by $\mathscr{E}_{n,q}$, and that he also considered q-Euler polynomials which are defined by

$$\mathscr{E}_{n,q}(x) = \sum_{l=0}^{n}\binom{n}{l}[x]_q^{n-l} q^{lx}\mathscr{E}_{l,q} \tag{3}$$

(see [1–5]).

Let $C(\mathbb{Z}_p)$ be the space of continuous $\mathscr{C}_p$-valued functions on $\mathbb{Z}_p$. For $f \in C(\mathbb{Z}_p)$, the fermionic p-adic q-integrals on $\mathbb{Z}_p$ are defined by Kim to be

$$\begin{aligned} I_{-q}(f) &= \int_{\mathbb{Z}_p} f(x)\, d\mu_{-q}(x) \\ &= \lim_{N\to\infty}\frac{1}{[p^N]_{-q}}\sum_{x=0}^{p^N-1} f(x)(-q)^x, \end{aligned} \tag{4}$$

where $[x]_{-q} = (1-(-q)^x)/(1+q)$ (see [1, 3, 4, 6–14]). From (2), he derived the following formula for Carlitz's q-Euler numbers.

The Changhee polynomials are defined by the generating function to be

$$\frac{2}{2+t}(1+t)^x = \sum_{n=0}^{\infty} Ch_n(x)\frac{t^n}{n!} \tag{5}$$

(see [15–23]).

In [16, 24], the authors (2017) obtained that

$$E_n(x)=\sum_{k=0}^{n} S_2(n,k)\, Ch_k(x), \tag{6}$$

$$Ch_n(x)=\sum_{k=0}^{n} S_1(n,k)\, E_k(x), \quad (n\ge 0) \tag{7}$$

(see [15, 16, 18–23]), where $S_1(n,k)$ is the Stirling numbers of the first kind and $S_2(n,k)$ is the Stirling numbers of the second kind as follows:

$$\begin{aligned}(x)_n &= x(x-1)\cdots(x-n+1)=\sum_{k=0}^{n} S_1(n,k)\, x^k,\\ \left(e^t-1\right)^m &= m!\sum_{k=m}^{\infty} S_2(k,m)\frac{t^k}{k!}, \quad (n\ge 0)\end{aligned} \tag{8}$$

(see [2, 10, 25–27]).

The degenerate Euler polynomials are defined by the generating function to be

$$\frac{2}{(1+\lambda t)^{1/\lambda}+1}(1+\lambda t)^{x/\lambda}=\sum_{n=0}^{\infty}\mathscr{E}_{n,\lambda}(x)\frac{t^n}{n!} \tag{9}$$

(see [3, 4]).

The degenerate q-Euler polynomials are defined by the generating function to be

$$\int_{\mathbb{Z}_p}(1+\lambda t)^{[x+y]_q/\lambda}\, d\mu_{-q}(y)=\sum_{n=0}^{\infty}\mathscr{E}_{n,q,\lambda}(x)\frac{t^n}{n!} \tag{10}$$

(see [3, 4]).

In [2, 26–28], Kim et al. (2017) defined the degenerate Stirling numbers of the second kind as follows:

$$\frac{1}{k!}\left((1+\lambda t)^{1/\lambda}-1\right)^k=\sum_{n=k}^{\infty}S_{2,\lambda}(n,k)\frac{t^n}{n!}, \tag{11}$$

where $k\in\mathbb{N}\cup\{0\}$ and $\lambda\in\mathbb{R}$. In [15], by using the fermionic p-adic q-integral on $\mathbb{Z}_p$, the authors defined Carlitz's type q-Changhee polynomials as follows:

$$\int_{\mathbb{Z}_p}(1+t)^{[x+y]_q}\, d\mu_{-q}(y)=\sum_{n=0}^{\infty}Ch_{n,q}(x)\frac{t^n}{n!} \tag{12}$$

(see [1, 2, 14, 15, 24, 29–31]).

In this paper, we define Carlitz's type modified degenerate q-Changhee polynomials and investigate some interesting identities of these polynomials.

2. Carlitz's Type Modified Degenerate q-Changhee Polynomials

In this section, we assume that $t\in\mathbb{C}_p$ with $|t|_p<p^{-1/(p-1)}$ and $|\lambda|_p<p^{-1/(p-1)}$. From (4) and (6), we note that

$$\begin{aligned}\int_{\mathbb{Z}_p}(1+t)^{x+y}\, d\mu_{-1}(y) &= \frac{2}{2+t}(1+t)^x\\ &= \sum_{n=0}^{\infty}Ch_n(x)\frac{t^n}{n!},\end{aligned} \tag{13}$$

$$1+t=e^{\log(1+t)}=\lim_{\lambda\to 0}\left(1+\lambda\log(1+t)\right)^{1/\lambda}. \tag{14}$$

In the viewpoint of (12) and (14), Carlitz's type modified degenerate q-Changhee polynomials are defined by

$$\begin{aligned}&\int_{\mathbb{Z}_p}(1+\lambda\log(1+t))^{[x+y]_q/\lambda}\, d\mu_{-q}(y)\\ &\quad=\sum_{n=0}^{\infty}Ch_{n,q,\lambda}(x)\frac{t^n}{n!}.\end{aligned} \tag{15}$$

We observe that

$$\begin{aligned}&(1+\lambda\log(1+t))^{[x+y]_q/\lambda}\\ &\quad=\sum_{k=0}^{\infty}\binom{\frac{1}{\lambda}[x+y]_q}{k}\lambda^k(\log(1+t))^k\\ &\quad=\sum_{k=0}^{\infty}\left(\frac{1}{\lambda}[x+y]_q\right)_k\lambda^k\frac{1}{k!}(\log(1+t))^k\\ &\quad=\sum_{k=0}^{\infty}\left(\frac{1}{\lambda}[x+y]_q\right)_k\lambda^k\sum_{m=k}^{\infty}S_1(m,k)\frac{t^m}{m!}\\ &\quad=\sum_{m=0}^{\infty}\sum_{k=0}^{m}S_1(m,k)\left(\frac{1}{\lambda}[x+y]_q\right)_k\lambda^k\frac{t^m}{m!}\\ &\quad=\sum_{m=0}^{\infty}\sum_{k=0}^{m}S_1(m,k)\sum_{l=0}^{k}\left(\frac{1}{\lambda}\right)^l[x+y]_q^l S_1(k,l)\lambda^k\frac{t^m}{m!}\\ &\quad=\sum_{m=0}^{\infty}\left(\sum_{k=0}^{m}\sum_{l=0}^{k}S_1(m,k)S_1(k,l)\lambda^{k-l}[x+y]_q^l\right)\frac{t^m}{m!}.\end{aligned} \tag{16}$$

From (15) and (16), we get

$$\begin{aligned}&\sum_{n=0}^{\infty}Ch_{n,q,\lambda}(x)\frac{t^n}{n!}=\int_{\mathbb{Z}_p}(1+\lambda\\ &\quad\cdot\log(1+t))^{[x+y]_q/\lambda}\, d\mu_{-q}(y)\\ &\quad=\sum_{n=0}^{\infty}\left(\sum_{k=0}^{n}\sum_{l=0}^{k}S_1(n,k)S_1(k,l)\lambda^{k-l}\right.\\ &\quad\left.\cdot\int_{\mathbb{Z}_p}[x+y]_q^l\, d\mu_{-q}(y)\right)\frac{t^n}{n!}\\ &\quad=\sum_{n=0}^{\infty}\left(\sum_{k=0}^{n}\sum_{l=0}^{k}S_1(n,k)S_1(k,l)\lambda^{k-l}\mathscr{E}_{l,q}(x)\right)\frac{t^n}{n!}.\end{aligned} \tag{17}$$

Thus, by (17), we get the following theorem.

Theorem 1. *For $n\ge 0$, one has*

$$Ch_{n,q,\lambda}(x)=\sum_{k=0}^{n}\sum_{l=0}^{k}S_1(n,k)S_1(k,l)\lambda^{k-l}\mathscr{E}_{l,q}(x). \tag{18}$$

Note that

$$\lim_{\lambda\to 0} Ch_{n,q,\lambda}(x) = \lim_{\lambda\to 0}\sum_{k=0}^{n}\sum_{l=0}^{k} S_1(n,k)\,\lambda^{k-l}\mathscr{E}_{l,q}(x) = \sum_{k=0}^{n} S_{n,k}\mathscr{E}_{k,q}(x) = Ch_{n,q}(x), \quad (19)$$

$$\int_{\mathbb{Z}_p}(1+t)^{[x+y]_q}\,d\mu_{-q}(y) = \sum_{n=0}^{\infty} Ch_{n,q}(x)\frac{t^n}{n!}. \quad (20)$$

Replacing t by $(1+\lambda\log(1+t))^{1/\lambda}-1$ in (20), we observe that

$$\begin{aligned}
&\int_{\mathbb{Z}_p}(1+\lambda\log(1+t))^{(1/\lambda)[x+y]_q}\,d\mu_{-q}(y) \\
&= \sum_{m=0}^{\infty} Ch_{m,q}(x)\frac{1}{m!}\left((1+\lambda\log(1+t))^{1/\lambda}-1\right)^m \\
&= \sum_{m=0}^{\infty} Ch_{m,q}(x)\sum_{k=m}^{\infty} S_{2,\lambda}(k,m)\frac{(\log(1+t))^k}{k!} \\
&= \sum_{k=0}^{\infty}\sum_{m=0}^{k} Ch_{m,q}(x)\,S_{2,\lambda}(k,m)\sum_{n=k}^{\infty} S_1(n,k)\frac{t^n}{n!} \\
&= \sum_{n=0}^{\infty}\left(\sum_{k=0}^{n}\sum_{m=0}^{k} Ch_{n,q}(x)\,S_{2,\lambda}(k,m)\,S_1(n,k)\right)\frac{t^n}{n!}.
\end{aligned} \quad (21)$$

From (15) and (21), we get the following theorem.

Theorem 2. *For $n \ge 0$, one has*

$$Ch_{n,q,\lambda}(x) = \sum_{k=0}^{n}\sum_{m=0}^{k} Ch_{m,q}(x)\,S_{2,\lambda}(k,m)\,S_1(n,k). \quad (22)$$

Replacing t by e^t-1 in (15), we get

$$\begin{aligned}
&\int_{\mathbb{Z}_p}(1+\lambda t)^{(1/\lambda)[x+y]_q}\,d\mu_{-q}(y) \\
&= \sum_{k=0}^{\infty} Ch_{k,q,\lambda}(x)\frac{1}{k!}\left(e^t-1\right)^k \\
&= \sum_{k=0}^{\infty} Ch_{k,q,\lambda}(x)\sum_{n=k}^{\infty} S_2(n,k)\frac{t^n}{n!} \\
&= \sum_{n=0}^{\infty}\left(\sum_{k=0}^{n} Ch_{k,q,\lambda}(x)\,S_2(n,k)\right)\frac{t^n}{n!}.
\end{aligned} \quad (23)$$

Note that

$$\int_{\mathbb{Z}_p}(1+\lambda t)^{(1/\lambda)[x+y]_q}\,d\mu_{-q}(y) = \sum_{n=0}^{\infty}\mathscr{E}_{n,q,\lambda}(x)\frac{t^n}{n!}. \quad (24)$$

From (23) and (24), we get the following theorem.

Theorem 3. *For $n \ge 0$, one has*

$$\mathscr{E}_{n,q,\lambda}(x) = \sum_{k=0}^{\infty} Ch_{k,q,\lambda}(x)\,S_2(n,k). \quad (25)$$

When $x=0$, $Ch_{n,q,\lambda} = Ch_{n,q,\lambda}(0)$ are called Carlitz's type modified degenerate q-Changhee number. We also observe that

$$\begin{aligned}
&\left((1+\lambda\log(1+t))^{1/\lambda}+1-1\right)^{[x+y]_q/\lambda} \\
&= \sum_{k=0}^{\infty}\binom{[x+y]_q/\lambda}{k}\left((1+\lambda\log(1+t))^{1/\lambda}-1\right)^k \\
&= \sum_{k=0}^{\infty}\left(\frac{[x+y]_q}{\lambda}\right)_k\frac{1}{k!} \\
&\cdot\left((1+\lambda\log(1+t))^{1/\lambda}-1\right)^k = \sum_{k=0}^{\infty}\left(\frac{[x+y]_q}{\lambda}\right)_k \\
&\cdot\sum_{m=k}^{\infty} S_{2,\lambda}(m,k)\frac{1}{m!}(\log(1+t))^m \\
&= \sum_{m=0}^{\infty}\left(\sum_{k=0}^{m}\left(\frac{[x+y]_q}{\lambda}\right)_k S_{2,\lambda}(m,k)\sum_{n=m}^{\infty} S_1(n,m)\right) \\
&\cdot\frac{t^n}{n!} \\
&= \sum_{n=0}^{\infty}\left(\sum_{m=0}^{n}\sum_{k=0}^{m} S_{2,\lambda}(m,k)\sum_{l=0}^{k} S_1(k,l)\,\lambda^{-l}[x+y]_q^l\right) \\
&\cdot\frac{t^n}{n!} \\
&= \sum_{n=0}^{\infty}\left(\sum_{m=0}^{n}\sum_{k=0}^{m}\sum_{l=0}^{k} S_{2,\lambda}(m,k)\,S_1(k,l)\,\lambda^{-l}[x+y]_q^l\right) \\
&\cdot\frac{t^n}{n!}.
\end{aligned} \quad (26)$$

From (26), we get

$$\begin{aligned}
&\sum_{n=0}^{\infty} Ch_{n,q,\lambda}(x)\frac{t^n}{n!} = \int_{\mathscr{Z}_p}\left((1+\lambda\log(1+t))^{1/\lambda}+1\right. \\
&\left.-1\right)^{[x+y]_q/\lambda}\,d\mu_{-q}(y) \\
&= \sum_{n=0}^{\infty}\left(\sum_{m=0}^{n}\sum_{k=0}^{m}\sum_{l=0}^{k} S_{2,\lambda}(m,k)\,S_1(k,l)\,\lambda^{-l}\right. \\
&\left.\cdot\int_{\mathscr{Z}_p}[x+y]_q^l\,d\mu_{-q}(y)\right)\frac{t^n}{n!}.
\end{aligned} \quad (27)$$

By (27), we get the following theorem.

Theorem 4. *For $n \geq 0$, one has*

$$Ch_{n,q,\lambda}(x) = \sum_{m=0}^{n} \sum_{k=0}^{m} \sum_{l=0}^{k} S_{2,\lambda}(m,k) S_{k,l} \lambda^{-l} \mathscr{E}_{l,q}(x). \quad (28)$$

3. Results and Discussions

This study was to define the modified degenerate q-Changhee polynomials in (15). Theorem 1 is an interesting identity between the modified degenerate q-Changhee polynomials and the q-Euler polynomials. Theorem 2 is that the modified degenerate q-Changhee polynomials is represented by a sum of products of the degenerate Stirling numbers of the second kind, the Stirling numbers of the first kind, and q-Changhee polynomials. Theorem 3 is an identity between the degenerate q-Euler polynomials and the modified degenerate q-Changhee polynomials. Theorem 4 is an identity between the modified degenerate q-Changhee polynomials and the q-Euler polynomials. In the future, we will study to define and to investigate the higher-order modified degenerate q-Changhee polynomials (see [3, 11]) and to investigate the symmetric identities of the modified degenerate q-Changhee polynomials (see [3, 11]).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed equally to this work. All authors read and approved the final manuscript.

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