Research Article

$q$-Bernstein Polynomials Associated with $q$-Stirling Numbers and Carlitz’s $q$-Bernoulli Numbers

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Recently, Kim (2011) introduced $q$-Bernstein polynomials which are different $q$-Bernstein polynomials of Phillips (1997). In this paper, we give a $p$-adic $q$-integral representation for $q$-Bernstein type polynomials and investigate some interesting identities of $q$-Bernstein type polynomials associated with $q$-extensions of the binomial distribution, $q$-Stirling numbers, and Carlitz’s $q$-Bernoulli numbers.

1. Introduction

Let $p$ be a fixed prime number. Throughout this paper, $\mathbb{Z}_p$, $\mathbb{Q}_p$, $\mathbb{C}$, and $\mathbb{C}_p$ denote the ring of $p$-adic integers, the field of $p$-adic rational numbers, the complex number field, and the completion of the algebraic closure of $\mathbb{Q}_p$, respectively. Let $\mathbb{N}$ be the set of natural numbers and $\mathbb{Z}_+ = \mathbb{N} \cup \{0\}$. Let $\nu_p$ be the normalized exponential valuation of $\mathbb{C}_p$ with $|p|_p = p^{-\nu_p(p)} = 1/p$.

When one talks of $q$-extensions, $q$ is variously considered as an indeterminate, a complex number $q \in \mathbb{C}$, or a $p$-adic number $q \in \mathbb{C}_p$. If $q \in \mathbb{C}$ then one normally assumes $|q| < 1$, and if $q \in \mathbb{C}_p$ then one normally assumes $|1-q|_p < 1$.

The $q$-bosonic natural numbers are defined by $[n]_q = (1-q^n)/(1-q) = 1 + q + q^2 + \cdots + q^{n-1}$ for $n \in \mathbb{N}$, and the $q$-factorial is defined by $[n]_q! = [n]_q[n-1]_q \cdots [2]_q[1]_q$ (see [1–3]). For the $q$-extension of binomial coefficients, we use the following notation in the form of

$$
{n \choose k}_q = \frac{[n]_q!}{[n-k]_q! [k]_q!} = \frac{[n]_q[n-1]_q \cdots [n-k+1]_q}{[k]_q!}.
$$

(1.1)
Let $C[0,1]$ denote the set of continuous functions on the real interval $[0,1]$. The Bernstein operator for $f \in C[0,1]$ is defined by

$$B_n(f \mid x) = \sum_{k=0}^{n} f \left( \frac{k}{n} \right) \binom{n}{k} x^k (1-x)^{n-k}$$

where $n, k \in \mathbb{Z}_+$. The polynomials $B_{k,n}(x) = \binom{n}{k} x^k (1-x)^{n-k}$ are called Bernstein polynomials of degree $n$ (see [4–8]). For $f \in C[0,1]$, $q$-Bernstein type operator of order $n$ for $f$ is defined by

$$B_{n,q}(f \mid x) = \sum_{k=0}^{n} f \left( \frac{k}{n} \right) \binom{n}{k} [x]_q^k [1-x]_q^{n-k}$$

where $n, k \in \mathbb{Z}_+$. Here $B_{k,n}(x, q) = \binom{n}{k} [x]_q^k [1-x]_q^{n-k}$ are called $q$-Bernstein type polynomials of degree $n$ (see [9]).

We say that $f$ is uniformly differentiable at a point $a \in \mathbb{Z}_p$ and write $f \in \text{UD}(\mathbb{Z}_p)$, if the difference quotient $F_f(x, y) = (f(x) - f(y)) / (x-y)$ has a limit $f'(a)$ as $(x, y) \to (a, a)$. For $f \in \text{UD}(\mathbb{Z}_p)$, the $p$-adic $q$-integral on $\mathbb{Z}_p$ is defined by

$$I_q(f) = \int_{\mathbb{Z}_p} f(x) d\mu_q(x) = \lim_{N \to \infty} \frac{1}{[p^N]_q} \sum_{x=0}^{p^N-1} f(x) q^x$$

(see [10]). Carlitz’s $q$-Bernoulli numbers can be represented by a $p$-adic $q$-integral on $\mathbb{Z}_p$ as follows:

$$\int_{\mathbb{Z}_p} [x]^a d\mu_q(x) = \lim_{N \to \infty} \frac{1}{[p^N]_q} \sum_{x=0}^{p^N-1} [x]^a q^x = \beta_{n,q}$$

(see [10, 11]). The $k$th order factorial of $[x]_q$ is defined by

$$[x]_{k,q} = [x]_q[x-1]_q \cdots [x-k+1]_q = \frac{(1-q^x)(1-q^{x-1})\cdots(1-q^{x-k+1})}{(1-q)^k}$$

and is called the $q$-factorial of $x$ of order $k$ (see [10]).

In this paper, we give a $p$-adic $q$-integral representation for $q$-Bernstein type polynomials and derive some interesting identities for the $q$-Bernstein type polynomials associated with the $q$-extension of binomial distributions, $q$-Stirling numbers, and Carlitz’s $q$-Bernoulli numbers.

2. $q$-Bernstein Polynomials

In this section, we assume that $0 < q < 1$. Let $\mathcal{F}_n = \{ \sum_i a_i [x]_q^i \mid a_i \in \mathbb{R} \}$ be the space of $q$-polynomials of degree less than or equal to $n$.
We claim that the \( q \)-Bernstein type polynomials of degree \( n \) defined by (1.3) are a basis for \( \mathbb{P}_{n,q} \).

First, we see that the \( q \)-Bernstein type polynomials of degree \( n \) span the space of \( q \)-polynomials. That is, any \( q \)-polynomials of degree less than or equal to \( n \) can be written as a linear combination of the \( q \)-Bernstein type polynomials of degree \( n \).

For \( n, k \in \mathbb{Z}_+ \) and \( x \in [0, 1] \), we have

\[
B_{k,n}(x, q) = \sum_{i=k}^{n} \binom{n}{i} \binom{i}{k} (-1)^{i-k} [x]_q^i
\]  
(2.1)

(see [9]). If there exist constants \( C_0, C_1, \ldots, C_n \) such that \( C_0 B_{0,n}(x, q) + C_1 B_{1,n}(x, q) + \cdots + C_n B_{n,n}(x, q) = 0 \) holds for all \( x \), then we can derive the following equation from (2.1):

\[
0 = C_0 B_{0,n}(x, q) + C_1 B_{1,n}(x, q) + \cdots + C_n B_{n,n}(x, q)
= C_0 \sum_{i=0}^{n} (-1)^i \binom{n}{i} \frac{[x]_q^i}{(i)_q} + C_1 \sum_{i=1}^{n} (-1)^{i-1} \binom{n}{i} \frac{[x]_q^i}{(1)_q}
+ \cdots + C_n \sum_{i=n}^{n} (-1)^{i-n} \binom{n}{i} \frac{[x]_q^i}{(n)_q}
\]

\[
= C_0 + \left\{ \sum_{i=0}^{n} C_i (-1)^{i-1} \binom{n}{1} \frac{[x]_q}{(i)_q} \right\} + \cdots + \left\{ \sum_{i=0}^{n} C_i (-1)^{i-n} \binom{n}{n} \frac{[x]_q^n}{(i)_q} \right\}
\]  
(2.2)

Since the power basis is a linearly independent set, it follows that

\[
C_0 = 0,
\]
\[
\sum_{i=0}^{1} C_i (-1)^{i-1} \binom{n}{1} \frac{[x]_q}{(i)_q} = 0,
\]
\[
\vdots
\]
\[
\sum_{i=0}^{n} C_i (-1)^{i-n} \binom{n}{n} \frac{[x]_q^n}{(i)_q} = 0,
\]  
(2.3)

which implies that \( C_0 = C_1 = \cdots = C_n = 0 \) (\( C_0 \) is clearly zero, substituting this in the second equation gives \( C_1 = 0 \), substituting these two into the third equation gives \( C_2 = 0 \), and so on). Hence, we have the following theorem.

**Theorem 2.1.** The \( q \)-Bernstein type polynomials of degree \( n \) are a basis for \( \mathbb{P}_{n,q} \).
Let us consider a $q$-polynomial $P_q(x) \in \mathbb{P}_{n,q}$ as a linear combination of $q$-Bernstein type basis functions as follows:

$$P_q(x) = C_0 B_{0,n}(x, q) + C_1 B_{1,n}(x, q) + \cdots + C_n B_{n,n}(x, q).$$  \hspace{1cm} (2.4)

We can write (2.4) as a dot product of two values:

$$P_q(x) = (B_{0,n}(x, q), B_{1,n}(x, q), \ldots, B_{n,n}(x, q)) \cdot \begin{pmatrix} C_0 \\ C_1 \\ \vdots \\ C_n \end{pmatrix}.$$  \hspace{1cm} (2.5)

From (2.5), we can derive the following equation:

$$P_q(x) = \left(1, [x]_q, \ldots, [x]^n_q\right) \begin{pmatrix} b_{00} & 0 & 0 & \cdots & 0 \\ b_{10} & b_{11} & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ b_{n0} & b_{n1} & b_{n2} & \cdots & b_{nn} \end{pmatrix} \begin{pmatrix} C_0 \\ C_1 \\ \vdots \\ C_n \end{pmatrix},$$  \hspace{1cm} (2.6)

where the $b_{ij}$ are the coefficients of the power basis that are used to determine the respective $q$-Bernstein type polynomials.

From (1.3) and (2.1), we note that

$$B_{0,2}(x, q) = [1 - x]^2_{1/q} = \sum_{l=0}^{2} \binom{2}{l}(-1)^l[x]^l_q = 1 - 2[x]_q + [x]^2_q,$$

$$B_{1,2}(x, q) = \binom{2}{1}[x]_q[1-x]_{1/q} = 2[x]_q - 2[x]^2_q,$$  \hspace{1cm} (2.7)

$$B_{2,2}(x, q) = \binom{2}{2}[x]^2_q = [x]^2_{q'},$$

In the quadratic case ($n = 2$), the matrix representation is

$$P_q(x) = \left(1, [x]_{q'}, [x]^2_q\right) \begin{pmatrix} 1 & 0 & 0 \\ -2 & 2 & 0 \\ 1 & -2 & 1 \end{pmatrix} \begin{pmatrix} C_0 \\ C_1 \\ C_2 \end{pmatrix}.$$  \hspace{1cm} (2.8)
In the cubic case \( n = 3 \), the matrix representation is

\[
P_q(x) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -3 & 3 & 0 & 0 \\ 3 & -6 & 3 & 0 \\ -1 & 3 & -3 & 1 \end{pmatrix} \begin{pmatrix} C_0 \\ C_1 \\ C_2 \\ C_3 \end{pmatrix}.
\]

In many applications of \( q \)-Bernstein polynomials, a matrix formulation for the \( q \)-Bernstein type polynomials seems to be useful.

Remark 2.2 (see [12]). All results of this section for \( q = 1 \) are well known in classical case (see Bernstein Polynomials by Joy).

3. \( q \)-Bernstein Polynomials, \( q \)-Stirling Numbers, and \( q \)-Bernoulli Numbers

In this section, we assume that \( q \in \mathbb{C}_p \) with \( |1 - q|_p < 1 \).

For \( f \in \text{UD}(\mathbb{Z}_p) \), let us consider the \( p \)-adic analogue of \( q \)-Bernstein type operator of order \( n \) on \( \mathbb{Z}_p \) as follows:

\[
\mathbb{B}_{n,q}(f \mid x) = \sum_{k=0}^{n} f\left(\frac{k}{n}\right) \left(\begin{array}{c} n \\ k \end{array}\right) [x]_q^k [1 - x]_q^{n-k} = \sum_{k=0}^{n} \frac{k}{n} B_{k,n}(x,q).
\]

Here \( B_{k,n}(x,q) \) is the \( q \)-Bernstein type polynomials of degree \( n \) on \( \mathbb{Z}_p \) defined by

\[
B_{k,n}(x,q) = \left(\begin{array}{c} n \\ k \end{array}\right) [x]_q^k [1 - x]_q^{n-k},
\]

for \( n, k \in \mathbb{Z}_+ \) and \( x \in \mathbb{Z}_p \).

Let \((Eh)(x) = h(x + 1)\) be the shift operator. Then the \( q \)-difference operator is defined by

\[
\Delta_q^n := (E - I)^n_q = \prod_{i=1}^{n} (E - q^{-1}I),
\]

where \((Ih)(x) = h(x)\). From (3.3), we derive the following equation:

\[
\Delta_q^n f(0) = \sum_{k=0}^{n} \left(\begin{array}{c} n \\ k \end{array}\right) (-1)^k q^{k\frac{k}{2}} f(n - k).
\]
By (3.4), we easily see that
\[
f(x) = \sum_{n \geq 0} \binom{x}{n} \Delta_q^n f(0)
\]  
(3.5)

(see [10, 11]).

The \(q\)-Stirling number of the first kind is defined by
\[
\prod_{k=1}^{n} \left(1 + \left\lfloor \frac{k}{q} \right\rfloor \right) = \sum_{k=0}^{n} S_1(q, n) z^k,
\]  
(3.6)

and the \(q\)-Stirling number of the second kind is also defined by
\[
\prod_{k=1}^{n} \left(\frac{1}{1 + \left\lfloor \frac{k}{q} \right\rfloor \cdot \left\lfloor \frac{k}{q} \right\rfloor} \right) = \sum_{k=0}^{n} S_2(q, n) z^k.
\]  
(3.7)

By (3.3), (3.4), (3.6), and (3.7), we get
\[
S_2(q, n, k) = \frac{q^{-\left(\frac{k}{q} \right)} \binom{k}{j}}{[k]_q} \sum_{j=0}^{k} (-1)^j q^{-\left(\frac{j}{q} \right)} \binom{k}{j} [k-j]_q^n = \frac{q^{-\left(\frac{k}{q} \right)} \binom{k}{j}}{[k]_q} \Delta_q^k 0^n,
\]  
(3.8)

for \(n, k \in \mathbb{Z}_+\) (see [10, 13]).

From the definition of \(q\)-Bernstein type polynomials of degree \(n\) on \(\mathbb{Z}_+\), we easily see that
\[
\int_{\mathbb{Z}_q} B_{n, q}(x, q) d\mu_q(x) = \sum_{l=0}^{n-k} \binom{n-k}{l} \binom{n}{k} (-1)^l \int_{\mathbb{Z}_q} [x]_q^{i+k} d\mu_q(x).
\]  
(3.9)

By (1.5) and (3.9), we obtain the following proposition.

**Proposition 3.1.** For \(n, k \in \mathbb{Z}_+\), one has
\[
\int_{\mathbb{Z}_q} B_{n, q}(x, q) d\mu_q(x) = \sum_{l=0}^{n-k} \binom{n-k}{l} \binom{n}{k} (-1)^l \beta_{l+k, q},
\]  
(3.10)

where \(\beta_{l+k, q}\) are the \((l+k)th\) Carlitz’s \(q\)-Bernoulli numbers.

From the definition of \(q\)-Bernstein polynomial, we note that
\[
\sum_{k=1}^{n} \binom{k}{i} B_{k, q}(x, q) = \sum_{k=0}^{i} q^{-\left(\frac{k}{q} \right)} \binom{x}{k} [k]_q \Delta_q^i S_2(q, k, i-k),
\]  
(3.11)
where \(i \in \mathbb{N}\). From the definition of \(q\)-binomial coefficient, we have

\[
\binom{n+1}{k}_q = \binom{n}{k-1}_q + q^k \binom{n}{k}_q = q^{n-k} \binom{n}{k-1}_q + \binom{n}{k}_q. \tag{3.12}
\]

By (3.12), we see that

\[
\int_{\mathbb{Z}_q} \binom{x}{n}_q d\mu_q(x) = \frac{(-1)^n}{[n+1]_q} q^{(n+1)-(n+1)} \tag{3.13}
\]

(see [10, 11]). From (1.5), (3.11), and (3.13), we obtain the following theorem.

**Theorem 3.2.** For \(n, k \in \mathbb{Z}_+\) and \(i \in \mathbb{N}\), one has

\[
\sum_{k=i}^{n} \sum_{l=0}^{n-k} \binom{k}{l} \binom{n-k}{l} (-1)^i \beta_{i+k,q} = q \sum_{k=0}^{i} \binom{k}{i} [k]_q ! S_{2,q}(k, i-k) \frac{(-1)^k}{[k+1]_q} q^{(k+1)-(k+1)}. \tag{3.14}
\]

It is easy to see that, for \(i \in \mathbb{N}\),

\[
\sum_{k=i}^{n} \binom{k}{i} B_{k,n}(x, q) = [x]^i. \tag{3.15}
\]

By (3.11) and (3.15), we easily get

\[
[x]^i_q = \sum_{k=0}^{i} \binom{k}{i} \binom{x}{k}_q [k]_q ! S_{2,q}(k, i-k) \tag{3.16}
\]

(see [10]). Thus, we have

\[
\int_{\mathbb{Z}_q} [x]^i_q d\mu_q(x) = \sum_{k=0}^{i} \binom{k}{i} [k]_q ! S_{2,q}(k, i-k) \int_{\mathbb{Z}_q} \binom{x}{k}_q d\mu_q(x) \tag{3.17}
\]

\[
= q \sum_{k=0}^{i} \frac{[k]_q ! S_{2,q}(k, i-k)}{[k+1]_q} \frac{(-1)^k}{[k+1]_q}. \tag{3.17}
\]

By (1.5) and (3.17), we obtain the following corollary.

**Corollary 3.3.** For \(n, k \in \mathbb{Z}_+\) and \(i \in \mathbb{N}\), one has

\[
\beta_{i,q} = q \sum_{k=0}^{i} [k]_q ! S_{2,q}(k, i-k) \frac{(-1)^k}{[k+1]_q}. \tag{3.18}
\]
It is known that
\[ S_{2,q}(n,k) = \frac{1}{(1-q)^k} \sum_{j=0}^{k} (-1)^{k-j} \binom{k+n}{j} \binom{n}{j} q \]
(3.19)

(see [10]) and
\[ \binom{n}{k} q = \sum_{j=0}^{n} \binom{n}{j} (q-1)^{j-k} S_{2,q}(k-j). \] (3.20)

By a simple calculation, we have that
\[ q^{nx} = \sum_{k=0}^{n} (q-1)^k \binom{k}{2} \binom{n}{k} [x]_{k,q} \]
\[ = \sum_{m=0}^{n} \left\{ \sum_{k=m}^{n} (q-1)^k \binom{n}{k} S_{1,q}(k,m) \right\} [x]_{q}^m, \] (3.21)
\[ q^{nx} = \sum_{m=0}^{n} \binom{n}{m} (q-1)^m [x]_{q}^m. \]

From (3.21), we note that
\[ \binom{n}{m} = \sum_{k=m}^{n} (q-1)^{-m+k} \binom{n}{k} S_{1,q}(k,m) \] (3.22)
(see [10]).

Thus, we obtain the following proposition.

**Proposition 3.4.** For \( n,k \in \mathbb{Z}_+ \), one has
\[ B_{k,n}(x,q) = \binom{n}{k} [x]_{q}^k [1-x]_{1/q}^{n-k} = \sum_{m=k}^{n} (q-1)^{-k+m} \binom{n}{m} S_{1,q}(m,k) [x]_{q}^m [1-x]_{1/q}^{n-k}. \] (3.23)

From the definition of the \( q \)-Stirling numbers of the first kind, we get
\[ q^\frac{n}{2} \binom{n}{n} [n]_{q}! = [x]_{n,q} q^{\frac{n}{2}} = \sum_{k=0}^{n} S_{1,q}(n,k) [x]_{q}^k. \] (3.24)

By (3.11) and (3.24), we obtain the following theorem.
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**Theorem 3.5.** For $n, k \in \mathbb{Z}_+$ and $i \in \mathbb{N}$, one has

$$
\sum_{k=i}^{n} \binom{n}{k} B_{k,n}(x, q) = \sum_{k=0}^{i} \sum_{l=0}^{k} S_{1,q}(k, l) S_{2,q}(k, i - k) [x]_q^l.
$$

(3.25)

By (3.15) and Theorem 3.5, we obtain the following corollary.

**Corollary 3.6.** For $i \in \mathbb{Z}_+$, one has

$$
\beta_{i,q} = \sum_{k=0}^{i} \sum_{l=0}^{k} S_{1,q}(k, l) S_{2,q}(k, i - k) \beta_{l,q}.
$$

(3.26)

The $q$-Bernoulli polynomials of order $k \in \mathbb{Z}_+$ are defined by

$$
\beta^{(k)}_{n,q}(x) = \frac{1}{(1-q)^n} \sum_{i=0}^{n} \binom{n}{i} (-1)^i q^{ix} \int \cdots \int \frac{q^{\sum_{i=1}^{k} (-1)^i x^i}}{[i+k]_q \cdots [i+1]_q} d\mu_q(x_1) \cdots d\mu_q(x_k).
$$

(3.27)

Thus, we have

$$
\beta^{(k)}_{n,q}(x) = \frac{1}{(1-q)^n} \sum_{i=0}^{n} \binom{n}{i} (-1)^i (i+k) \cdots (i+1) q^{ix}
$$

(3.28)

(see [10]). The inverse $q$-Bernoulli polynomials of order $k$ are defined by

$$
\beta^{(-k)}_{n,q}(x) = \frac{1}{(1-q)^n} \sum_{i=0}^{n} \binom{n}{i} (-1)^i \frac{q^{ix}}{i+k} \cdots \frac{q^{ix}}{i+1} d\mu_q(x_1) \cdots d\mu_q(x_k).
$$

(3.29)

In the special case $x = 0$, $\beta^{(k)}_{n,q}(0) = P^{(k)}_{n,q}$ are called the $n$th $q$-Bernoulli numbers of order $k$, and $\beta^{(-k)}_{n,q}(0) = \beta^{(-k)}_{n,q}$ are also called the inverse $q$-Bernoulli numbers of order $k$ (see [10]).

From (3.29), we have

$$
\beta^{(-n)}_{k,q} = \frac{1}{(1-q)^k} \sum_{j=0}^{k} (-1)^j \binom{k}{j} [j+n]_q [j+1]_q \cdots [j+1]_q (j+n) \cdots (j+1)
$$

$$
= \frac{1}{(1-q)^k} \sum_{j=0}^{k} (-1)^j \binom{k+n}{j} \binom{n}{j} \frac{[n]_q!}{n!}
$$

$$
= \frac{[n]_q!}{(k+n) n!} \left\{ \frac{1}{(1-q)^k} \sum_{j=0}^{k} (-1)^j \binom{k+n}{j} \binom{n}{j} \binom{j+n}{n} \right\}.
$$

(3.30)
By (3.19) and (3.30), we get
\[
\frac{n!}{[n]_q} \binom{k + n}{n} P_{k,q}^{(-n)} = S_{2,q}(n, k). \tag{3.31}
\]
Therefore, by (3.11) and (3.31), we obtain the following theorem.

**Theorem 3.7.** For \(i, n, k \in \mathbb{Z}_+\), one has
\[
\sum_{k=1}^{n} \frac{\binom{k}{n}}{n!} B_{k,n}(x,q) = \sum_{k=0}^{i} q^k k! \binom{i}{k} (x) \frac{1}{k_q} P_{i-k,q}^{(-k)}. \tag{3.32}
\]

It is easy to show that
\[
q^\left(\begin{array}{l}
\binom{x}{n} \\
q\end{array}\right) = \frac{1}{[n]_q} \prod_{k=0}^{n-1} ([x]_k - [k]_q) = \frac{1}{[n]_q} \sum_{k=0}^{n} (-1)^k [x]_q^{-k} S_{1,q}(n - 1, k). \tag{3.33}
\]
Thus, we have that
\[
\sum_{k=1}^{n} \frac{\binom{k}{n}}{n!} B_{k,n}(x,q) = \sum_{k=0}^{i} \sum_{j=0}^{k} (-1)^j [x]_q^{-k-j} S_{1,q}(k - 1, j) \frac{k!}{[k]_q} \binom{i}{k} \frac{1}{k_q} P_{i-k,q}^{(-k)}. \tag{3.34}
\]
where \(n, k, i \in \mathbb{Z}_+\).

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**References**


