A RAMANUJAN-TYPE MEASURE FOR THE ASKEY-WILSON POLYNOMIALS

Natig M. Atakishiyev
Instituto de Investigaciones en Matemáticas Aplicadas y en Sistemas - Cuernavaca
Universidad Nacional Autónoma de México
Apartado Postal 139-B
62191 Cuernavaca, Morelos, México
e-mail: natig@ce.ifisicam.unam.mx

Abstract

A Ramanujan-type representation for the Askey-Wilson $q$-beta integral, admitting the transformation $q \to q^{-1}$, is obtained. Orthogonality of the Askey-Wilson polynomials with respect to a measure, entering into this representation, is proved. A simple way of evaluating the Askey-Wilson $q$-beta integral is also given.

1 Introduction.

The Askey-Wilson polynomials $p_n(x; a, b, c, d|q)$ [1], which have already become classical, represent a five-parameter system of polynomials. They satisfy the orthogonality relation

$$\int_{-1}^{1} p_m(x; a, b, c, d|q) p_n(x; a, b, c, d|q) w(x; a, b, c, d|q) \, dx = \delta_{mn} I_n(a, b, c, d|q)$$

(1.1)

with respect to the absolutely continuous measure $d\alpha(x) = w(x)dx$, with the weight function

$$w(x; a, b, c, d|q) = \frac{1}{\sin \theta \prod_{j=a,b,c,d} h(\cos \theta, v; q)}$$

(1.2)

$$h(a, b; q) = \prod_{j=0}^{\infty} (1 - 2abq^j + b^2 q^{2j}) .$$

As special and limiting cases, the Askey-Wilson polynomials contain many known systems of polynomials (see, for example, [2]). In particular, the choice of the parameters $a = -b = \sqrt{\beta}$, $c = -d = \sqrt{q \beta}$, leads to the continuous $q$-ultraspherical polynomials $C_n(x; \beta|q)$ [3], i.e.,

$$p_n(x; \sqrt{\beta}, -\sqrt{\beta}, \sqrt{q \beta}, -\sqrt{q \beta}|q) = \frac{(\beta^2; q)_{2n} (q; q)^n}{(\beta, \beta^2; q)_{n}} C_n(x; \beta|q),$$

(1.3)

where we have used the standard notation of the theory of $q$-special functions

$$\frac{(a;q)_n}{(1-aq^j)}, \quad \prod_{j=1}^{k}(a_j;q)_n.$$

In turn, from $C_n(x;\beta|q)$ one can obtain the continuous $q$-Hermite polynomials $H_n(x|q) = (q;q)_n C_n(x;0|q)$, the Gegenbauer (ultraspherical) polynomials $C_n^\lambda(x) = \lim_{\gamma \rightarrow -1} C_n(x;\gamma^\lambda|q)$, and also the Chebyshev polynomials of the first and second kinds, $T_n(x)$ and $U_n(x)$, by taking the limit $\beta \rightarrow 1$ or by putting $\beta = q$ in $C_n(x;\beta|q)$, respectively.

The key ingredient of the original proof of the orthogonality (1.1), which led to the discovery of the Askey-Wilson system of polynomials (see the discussion of this point in [4]), was the evaluation of the Askey-Wilson $q$-beta integral:

$$I_0(a,b,c,d|q) \equiv \int_{-1}^{1} w(x;a,b,c,d|q) dx = \frac{2\pi(abcd;q)_\infty}{(q, ab, ac, ad, bc, bd, cd; q)_\infty},$$

$$\max_{v=a,b,c,d}|v| < 1, \quad |q| < 1.$$  \hfill (1.5)

The integral (1.5) has acquired its name because in a special case, when the parameters $a = q^\alpha + \frac{1}{2}$, $b = -q^{\beta + 1/2}$, and $c = -d = q^{1/2}$, the $q \rightarrow 1$ limit of $I_0(a,b,c,d|q)$ is the beta function (or Euler's integral of the first kind)

$$\int_{-1}^{1} (1-x)^{\alpha}(1+x)^{\beta} dx = 2^{\alpha + \beta + 1}B(\alpha + 1, \beta + 1) = 2^{\alpha + \beta + 1} \frac{\Gamma(\alpha + 1)\Gamma(\beta + 1)}{\Gamma(\alpha + \beta + 2)}. \hfill (1.6)$$

A nonstandard form of the orthogonality on the full real line for the continuous $q$-Hermite polynomials $H_n(\sin \xi|x|q)$, $q = \exp(-2\kappa^2)$, was considered in [5]. It turned out that if one uses the modular transformation and the periodicity property of the $\vartheta$-function appearing in the weight function for these polynomials, the finite interval of orthogonality can be transformed into an infinite one. This technique is of interest both from a mathematical point of view and from the point of view of possible applications in theoretical physics, beginning with a number of problems, related with $q$-oscillators (see the review [6]).

The purpose of this article is to discuss the applicability of this idea to the more general case, i.e. to the Askey-Wilson $q$-beta integral (1.5) [7, 8]. To simplify consideration it will be assumed in Sections 2-4 that $|v| < 1$, $v = a, b, c, d$, and that the parameter $q = \exp(-2\kappa^2)$ satisfies the requirement $0 < q < 1$. The possibility of extending these results to other values of the parameters is discussed in Section 5.

2 A Ramanujan-type representation for the $q$-beta integral.

From the point of view of symmetry the parametrization $x = \sin \varphi$ is most convenient; it corresponds to the change of variable $\theta = \frac{\pi}{2} - \varphi$, $-\frac{\pi}{2} \leq \varphi \leq \frac{\pi}{2}$ in formula (1.2). Consequently, the left
side of (1.5) is equal to

\[ I_0(a, b, c, d|q) = \int_{-\pi/2}^{\pi/2} \frac{h(-\cos 2\varphi, 1; q)}{\prod_{v=a,d,c,d} h(\sin \varphi, v; q)}
\]

Comparison of the numerator

\[ h(-\cos 2\varphi, 1; q) = \prod_{j=0}^{\infty} (1 + 2q^j \cos 2\varphi + q^{2j}) \]

of the integral (2.1) with Jacobi's expression for the theta-function \( \vartheta_2(z, q) \equiv \vartheta_2(z|\tau) \), \( q = \exp(\pi i \tau) \) as an infinite product [9]

\[ \vartheta_2(z, q) = 2q^{1/4}(q^2; q^2)_{\infty} \cos z \prod_{j=1}^{\infty} (1 + 2q^{2j} \cos 2z + q^{4j}) \]

shows that

\[ h(-\cos 2\varphi, 1; q) = \frac{2\cos \varphi}{q^{1/8}(q, q)_{\infty}} \vartheta_2(\varphi, q^{1/2}) \]

and therefore

\[ I_0(a, b, c, d|q) = \frac{2}{q^{1/8}(q, q)_{\infty}} \int_{-\pi/2}^{\pi/2} \frac{\vartheta_2(\varphi, q^{1/2}) \cos \varphi}{\prod_{v=a,b,c,d} h(\sin \varphi, v; q)} d\varphi. \]

With the aid of the modular transformation [9]

\[ \vartheta_2(z|\tau) = \frac{\exp(-iz^2)}{(-i\tau)^{1/2}} \vartheta_4(z\tau^{-1}|\tau^{-1}), \quad \tau = \frac{i\kappa^2}{\pi}, \]

and the change of variable \( \varphi = \kappa x \), the integral (2.4) can be written as

\[ I_0(a, b, c, d|q) = \frac{2\sqrt{\pi}}{q^{1/8}(q, q)_{\infty}} \int_{-\pi/2\kappa}^{\pi/2\kappa} \frac{\vartheta_4(\frac{\pi i}{\kappa} x, e^{-\pi^2/\kappa^2}) e^{-x^2 \cos \kappa x}}{\prod_{v=a,b,c,d} h(\sin \kappa x, v; q)}
\]

Using the expansion

\[ \vartheta_4(z, q) = \sum_{k=-\infty}^{\infty} (-1)^k q^{k^2} e^{2ikz} \]

and taking into account the uniform convergence of the series (2.7) in any bounded domain of values of \( z \) [9], we substitute (2.7) into (2.6) and integrate this series termwise, i.e.,

\[ I_0(a, b, c, d|q) = \frac{2\sqrt{\pi}}{q^{1/8}(q, q)_{\infty}} \sum_{k=-\infty}^{\infty} (-1)^k \int_{-\pi/2\kappa}^{\pi/2\kappa} e^{-(x+\pi/\kappa)^2} \cos \kappa x dx \]

\[ \prod_{v=a,b,c,d} h(\sin \kappa x, v; q). \]
The change of variable $x_k = x + \frac{\pi}{k}$, $x_k^\text{min} = \frac{\pi}{k}(k - \frac{1}{2}) \leq x_k \leq \frac{\pi}{k}(k + \frac{1}{2}) = x_k^\text{max}$ and an account for the relation $x_k^\text{max} = x_k^\text{min}$ allows to sum the right-hand side of (2.8) with respect to $k$ and represent (2.8) in the form

$$I_0(a, b, c, d|q) = \frac{2\sqrt{\pi}}{q^{1/8}(q; q)_\infty} I_0(a, b, c, d|q) = \frac{2\sqrt{\pi}}{q^{1/8}(q; q)_\infty} \int_{-\infty}^{\infty} e^{-x^2} \cos kx dx,$$

Thus, combining formulas (1.5) and (2.9) yields the following representation for the Askey-Wilson $q$-beta integral [7]

$$\tilde{I}_0(a, b, c, d|q) \equiv \int_{-\infty}^{\infty} \rho(\kappa x; a, b, c, d|q) e^{-x^2} \cos kx dx = \frac{\sqrt{\pi}q^{1/4}(abcd; q)_\infty}{(ab, ac, ad, bc, bd, cd; q)_\infty},$$

where, in accordance with the definition (1.2),

$$\rho(x; a, b, c, d|q) = \prod_{v=a,b,c,d} h^{-1}(\sin x, v; q) = \prod_{v=a,b,c,d} e_q(i\nu e^{-ix})e_q(-ive^{ix}),$$

and $e_q(z) = (z; q)_\infty^{-1}$ is the $q$-exponential function [2].

We note that each factor $h^{-1}(\sin kx, v; q)$, $v = a, b, c, d$, in the integrand (2.10) is represented as

$$h^{-1}(\sin kx, v; q) = \sum_{n=0}^{\infty}(iv)^n \sum_{k=0}^{n} (-1)^k \exp[-i(n - 2k)kx],$$

if one uses the generating function for the continuous $q$-Hermite polynomials $H_n(x|q)$

$$(te^{i\theta}, te^{-i\theta}; q)_\infty^{-1} = \sum_{n=0}^{\infty} \frac{H_n(\cos \theta|q)}{(q; q)_n} t^n, |t| < 1,$$

and their explicit representation [2]

$$H_n(\cos \theta|q) = \sum_{k=0}^{n} \left[ \frac{n}{k} \right]_q e^{i(n-2k)\theta},$$

where the symbol $\left[ \frac{n}{k} \right]_q$ denotes the $q$-binomial coefficient [2]. Therefore the integration over $x$ in (2.10) is reduced to the Fourier transformation formula for the ground state of the linear harmonic oscillator

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp(-x^2/2 + ixy) dx = \exp(-y^2/2).$$

An explicit evaluation of the nonstandard form of the Askey-Wilson $q$-beta integral (2.10) will be discussed in greater detail in Section 4.

As mentioned above, the weight function (1.2) with the parameters $a = -b = \beta 1/2$, $c = -d = aq^{1/2}$, corresponds to the continuous $q$-ultraspherical polynomials $C_n(x; \beta|q)$. The relations [2]

$$(a; q)_\infty = (a, aq; q^2)_\infty, \quad (a, -a; q)_\infty = (a^2, q^2)_\infty,$$
enable the representation (2.10) for this particular case to be simplified to
\[
\int_{-\infty}^{\infty} \frac{\exp(-x^2 + ikx)dx}{(-\beta \exp(2ikx), -\beta \exp(-2ikx); q)_{\infty}} = \frac{\sqrt{\pi q^{1/4}(\beta, q\beta; q)_{\infty}}}{(\beta^2; q)_{\infty}}. \tag{2.16}
\]

If one compares (2.16) with the Ramanujan integral \( q = \exp(-2k^2), |q| < 1 \) [10, 11]
\[
\int_{-\infty}^{\infty} e^{-x^2+2mx} e_q(aq^{1/2}e^{2ikx})c_q(bq^{1/2}e^{-2ikx}) dx = \frac{\sqrt{\pi e^{n^2}q^{n^2}(1-q^n)(1-abcdq^{n-1})}}{(qab; q)_{\infty}} E_q(aq e^{2imk})E_q(bq e^{-2imk}), \tag{2.17}
\]

it is easy to verify that (2.16) agrees with (2.17) if one sets \( 2m = ik = i\kappa \) and \( a = b = -\beta q^{1/2} \).

### 3 Orthogonality of the Askey-Wilson polynomials with respect to the measure \( \rho(\kappa x; a, b, c, d|q) \).

A direct proof of the orthogonality for the Askey-Wilson polynomials
\[
\int_{-\infty}^{\infty} p_m(\sin \kappa x; a, b, c, d|q)p_n(\sin \kappa x; a, b, c, d|q) \rho(\kappa x; a, b, c, d|q) \exp(-x^2) \cos \kappa x dx =
\]
\[
= \delta_{mn} \tilde{I}_n(a, b, c, d|q) \tag{3.1}
\]

with respect to the weight function appearing in the nonstandard integral representation (2.10), is analogous to the proof of eigenfunctions orthogonality for the Sturm-Liouville differential equation [12]. Indeed, the difference differentiation formula for the Askey-Wilson polynomials [1]
\[
\sin \kappa \partial_x p_n(\sin \kappa x; a, b, c, d|q) = \tag{3.2}
\]
\[
= q^{-n/2}(1 - q^n)(1 - abcdq^{n-1}) \cos \kappa x p_{n-1}(\sin \kappa x; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q)
\]
provides a lowering operator for these polynomials. To find a raising operator one can use the relation
\[
w(\sin \varphi; a, b, c, d|q) = \frac{2\partial_2(\varphi, q^{1/2})}{q^{1/8}(q; q)_{\infty}} \rho(\varphi; a, b, c, d|q), \tag{3.3}
\]
which follows from (1.2), (2.3) and (2.11), and write the difference equation for the Askey-Wilson polynomials [1] in the form
\[
\sin \kappa \partial_x \left[ \frac{\vartheta_2(\kappa x, q^{1/2})}{\cos \kappa x} \rho(\kappa x; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q) \sin \kappa \partial_x p_n(\sin \kappa x; a, b, c, d|q) \right] =
\]
\[
= (1 - q^{-n})(1 - abcdq^{n-1}) \cos \kappa x \vartheta_2(\kappa x, q^{1/2}) \rho(\kappa x; a, b, c, d|q) p_n(\sin \kappa x; a, b, c, d|q). \tag{3.4}
\]
Now, using the difference differentiation formula (3.2) in the left-hand side of (3.4) and the periodicity property of the \( \vartheta_2 \)-function \[9\],

\[
\vartheta_2(z \pm \pi \tau, q) = q^{-1} \exp(\mp 2iz) \vartheta_2(z, q), \quad q = \exp(\pi i \tau),
\]

we arrive at the raising operator

\[
(p(\sin \kappa x \cos \kappa \partial_x - \cos \kappa x \sin \kappa \partial_x)) p_{n-1}(\sin \kappa x; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q)
\]

\[
= q^{1-n} \cos \kappa x \rho(\kappa x; a, b, c, d|q) p_n(\sin \kappa x; a, b, c, d|q). \quad (3.5)
\]

We are now in a position to give a direct proof of the orthogonality relation (3.1). We multiply both sides of the equality (3.6) by \( p_m(\sin \kappa x; a, b, c, d|q) \exp(-x^2) \) and integrate in \( x \) over the full real line. As a result we obtain in the right-hand side,

\[
q^{1-n} \int_{-\infty}^{\infty} dx p_m(\sin \kappa x; a, b, c, d|q) p_n(\sin \kappa x; a, b, c, d|q) \rho(\kappa x; a, b, c, d|q) e^{-x^2} \cos \kappa x dx \equiv
\]

\[
q^{1-n} I_{mn}(a, b, c, d|q). \quad (3.7)
\]

The left-hand side

\[
\int_{-\infty}^{\infty} dx p_m(\sin \kappa x; a, b, c, d|q) e^{-x^2} (\sin 2\kappa x \cos \kappa \partial_x - \cos 2\kappa x \sin \kappa \partial_x)
\]

\[
\rho(\kappa x; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q) p_{n-1}(\sin \kappa x; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q), \quad (3.8)
\]

can be integrated by parts with the aid of (3.2) and the evident relations

\[
\int_{-\infty}^{\infty} dx f(x) \cos \kappa \partial_x \varphi(x) = \int_{-\infty}^{\infty} dx \varphi(x) \cos \kappa \partial_x f(x),
\]

\[
\int_{-\infty}^{\infty} dx f(x) \sin \kappa \partial_x \varphi(x) = -\int_{-\infty}^{\infty} dx \varphi(x) \sin \kappa \partial_x f(x),
\]

which apply to (3.8) because the function \( \rho(\kappa x; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q) \) has no singularities inside of the strip \(-\kappa \leq y \leq \kappa, \quad -\infty < x < \infty \) in the complex plane \( z = x + iy \). This leads to

\[
q^{1-m} (1 - q^m)(1 - abcdq^{m-1}) I_{m-1n-1}(aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q). \quad (3.9)
\]

Equating the right-hand (3.7) and left-hand (3.10) sides thus yields

\[
q^{m-n} I_{mn}(a, b, c, d|q) = (1 - q^m)(1 - abcdq^{m-1}) I_{m-1n-1}(aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q). \quad (3.11)
\]
We now interchange \(m\) and \(n\) in (3.11) and take into account that the integral \(I_{mn}(a, b, c, d|q)\) is symmetric in \(m\) and \(n\) due to the definition (3.7), i.e.,

\[
q^{\frac{n-m}{2}}I_{mn}(a, b, c, d|q) = (1 - q^n)(1 - abcdq^{m-1})I_{m-1n-1}(aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q).
\]

(3.11')

Finally, multiplying both sides of (3.11) by \((1 - q^n)(1 - abcdq^{m-1})\) and of (3.11') by \((1 - q^m)(1 - abcdq^{m-1})\) and subtracting the second expression from the first, we get

\[
(q^{\frac{n-m}{2}} - q^{\frac{m-n}{2}})(1 - abcdq^{n+m-1})I_{mn}(a, b, c, d|q) = 0.
\]

(3.12)

From (3.12) it follows that \(I_{mn}(a, b, c, d|q) = \delta_{mn}I_n(a, b, c, d|q)\), confirming the orthogonality (3.1) of the Askey-Wilson polynomials for \(m \neq n\) [8].

We note that as special and limiting cases, (3.1) contains the orthogonality relations for other known sets of polynomials, such as the continuous \(q\)-ultraspherical polynomials \(C_n(x; \alpha|q)\), the continuous \(q\)-Hermite polynomials \(H_n(x; q) = (q; q)_nC_n(x; 0|q)\) (the corresponding special case of (3.1), when the all parameters \(a, b, c, d\) are equal to zero, is considered in [5]), the Chebyshev polynomials of the first and second kinds, \(T_n(x)\) and \(U_n(x)\), and so on.

4 Evaluation of the integrals \(\tilde{I}_n(a, b, c, d|q)\).

Iterating the recurrence relation

\[
\tilde{I}_n(a, b, c, d|q) = (1 - q^n)(1 - abcdq^{n-1})\tilde{I}_{n-1}(aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q),
\]

(4.1)

which follows from (3.11) or (3.11') when \(m = n\), allows to express the normalization integrals \(\tilde{I}_n(a, b, c, d|q)\), \(n = 1, 2, \ldots\), through a known value of the Askey-Wilson \(q\)-beta integral \(I_0(a, b, c, d|q)\), i.e.

\[
\tilde{I}_n(a, b, c, d|q) = \frac{(q, ab, ac, ad, bc, bd, cd; q)_n}{(1 - abcdq^{2n-1})(abcd; q)_{n-1}}\tilde{I}_0(a, b, c, d|q).
\]

(4.2)

It only remains to evaluate the integral \(\tilde{I}_0(a, b, c, d|q)\) itself. To this end, having defined the symmetrical \(\rho_+(x)\) and antisymmetrical \(\rho_-(x)\) combinations with respect to the inversion \(x \rightarrow -x\),

\[
\rho_\pm(x; a, b, c, d|q) = \frac{1}{2}[\rho(x; a, b, c, d|q) \pm \rho(-x; a, b, c, d|q)],
\]

(4.3)

it is convenient to rewrite (2.10) as

\[
\tilde{I}_0(a, b, c, d|q) = \int_{-\infty}^{\infty} dx \exp(-x^2 + i\kappa x)\rho_+(\kappa x; a, b, c, d|q).
\]

(4.4)

Let us carry out the replacements \(v \rightarrow v\sqrt{q}\), \(v = a, b, c, d\), and the subsequent shift of the variable of integration \(x \rightarrow x + i\kappa\) in (4.4). (We remind that the function \(\rho(\kappa z; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q)\) does not have singularities in the strip \(-\kappa \leq y \leq \kappa, \ -\infty < x < \infty\) of the complex plane \(z = x + iy\). Then, taking into account that in accordance with the definitions (1.2) and (2.11)

\[
\rho(\kappa(x + i\kappa); aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q) = \rho(\kappa x; a, b, c, d|q) \prod_{v=a,b,c,d} (1 + iv \exp(i\kappa x)),
\]

(4.5)
we obtain

\[ I_0(aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q) = (1 - s_2)I_0(a, b, c, d|q) + \]

\[ + s_4 \int_{-\infty}^{\infty} dx \exp(-x^2 + 3i\kappa x)\rho_+(\kappa x; a, b, c, d|q) - is_3 \int_{-\infty}^{\infty} dx \exp(-x^2 + 2i\kappa x)\rho_-(\kappa x; a, b, c, d|q), \]

where

\[ s_2 = ab + ac + ad + bc + bd + cd, \]

\[ s_3 = abc + abd + acd + bcd, \quad s_4 = abcd. \]

It remains only to express the second and third integrals in the right-hand side of (4.6) in terms of \( I_0(a, b, c, d|q) \). To that end one can use the \( n = 1 \) case of (3.6)

\[ (\sin 2\kappa x \cos \kappa \partial_x - \cos 2\kappa x \sin \kappa \partial_x)\rho(\kappa x; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q) = \]

\[ = [(1 - s_4)\sin 2\kappa x + (s_3 - s_1)\cos \kappa x]\rho(\kappa x; a, b, c, d|q), \]

taking into account that \( p_0(x; a, b, c, d|q) = 1 \), \( p_1(x; a, b, c, d|q) = 2(1 - s_4)x + s_3 - s_1 \) and \( s_1 = a + b + c + d \). The symmetrization of (4.8) leads to the relations

\[ (\sin 2\kappa x \cos \kappa \partial_x - \cos 2\kappa x \sin \kappa \partial_x)\rho_\pm(\kappa x; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q) = \]

\[ = (1 - s_4)\sin 2\kappa x \rho_\pm(\kappa x; a, b, c, d|q) + (s_3 - s_1)\cos \kappa x \rho_\mp(\kappa x; a, b, c, d|q). \]

Multiplying both sides of the equality (4.9) for the antisymmetrical combination \( \rho_-(\kappa x) \) by \( \exp(-x^2) \) and integrating over the variable \( x \) yields

\[ (1 - s_4) \int_{-\infty}^{\infty} dx \exp(-x^2 + 2i\kappa x)\rho_-(\kappa x; a, b, c, d|q) = i(s_1 - s_3)I_0(a, b, c, d|q). \]

(4.10)

Now we multiply both sides of (4.9) for \( \rho_+(\kappa x; aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q) \) by \( \exp(-x^2 + i\kappa x) \) and integrate over \( x \). Using (4.10), the result can be written as

\[ \int_{-\infty}^{\infty} dx \exp(-x^2 + 3i\kappa x)\rho_+(\kappa x; a, b, c, d|q) = \]

\[ = \left[ 1 - \frac{(s_3 - s_1)^2}{(1 - s_4)^2} \right] I_0(a, b, c, d|q) - \frac{1 - q}{1 - s_4} I_0(aq^{1/2}, bq^{1/2}, cq^{1/2}, dq^{1/2}|q). \]

(4.11)
Substituting (4.10) and (4.11) into (4.6), we find

\((1 - abcd)(1 - qabcd) I_0(a q^{1/2}, b q^{1/2}, c q^{1/2}, d q^{1/2}|q) = \)

\((1 - ab)(1 - ac)(1 - ad)(1 - bc)(1 - bd)(1 - cd) I_0(a, b, c, d|q). \)  

(4.12)

Since \(0 < q < 1\), by iterating equation (4.12) one can express the Askey-Wilson \(q\)-beta integral (2.10) with arbitrary parameters in terms of its value for vanishing parameters \(a, b, c, d\), i.e.,

\[ I_0(a, b, c, d|q) = \frac{(abcd; q)_\infty}{(ab, ac, ad, bc, bd, cd; q)_\infty} I_0(0, 0, 0, 0|q). \]  

(4.13)

The value of \(I_0(0, 0, 0, 0|q)\) is easily found from (2.10) and (3.1) with the aid of the Fourier transformation formula (2.15) for the quadratically decreasing exponential function, i.e.,

\[ I_0(0, 0, 0, 0|q) = \int_{-\infty}^{\infty} dx \exp(-x^2 + i\kappa x) = \sqrt{\pi} q^{1/8}. \]  

(4.14)

Combining formulas (4.13) and (4.14) leads to

\[ I_0(a, b, c, d|q) = \frac{\sqrt{\pi} q^{1/8}(abcd; q)_\infty}{(ab, ac, ad, bc, bd, cd; q)_\infty}, \]  

(4.15)

which is the known value of the Askey-Wilson \(q\)-beta integral [1]

\[ I_0(a, b, c, d|q) = \frac{2\sqrt{\pi}}{q^{1/8}(q; q)_\infty} I_0(a, b, c, d|q) = \frac{2\pi (abcd; q)_\infty}{(q, ab, ac, ad, bc, bd, cd; q)_\infty}. \]  

(4.15')

Substituting (4.15) into (4.2), we finally obtain the explicit form for the normalization integral

\[ \bar{I}_n(a, d, c, d|q) = \frac{\sqrt{\pi} q^{1/8}(q; q)_n(abcdq^{n-1}; q)_\infty}{(1 - abcdq^{2n-1})(abq^n, acq^n, adq^n, bq^{n+1}, bdq^n, cdq^n; q)_\infty}. \]  

(4.16)

The complications arising in the evaluation of the standard form of the Askey-Wilson \(q\)-beta integral (1.5) can be illustrated by the following short quotation from reference [4]: "This was surprisingly hard, and it has taken over five years before relatively simple ways of evaluating this integral were found".

5 The transformation \(q \rightarrow q^{-1}\)

It is necessary to emphasize that the nonstandard orthogonality relation (3.1) admits the transformation \(q \rightarrow q^{-1} [7, 8]\). The standard form of the Askey-Willson integral (1.5) does not in general have this property. Even in the simplest case of vanishing parameters \(a, b, c\) and \(d\), which corresponds to the continuous \(q\)-Hermite polynomials \(H_n(x|q)\), the definition of a weight function for the system of polynomials \(h_n(x; q) = i^{-n} H_n(ix|q^{-1})\) requires a special analysis [13, 14].
Since

\[(z; q^{-1})_\infty = (qz; q^{-1})_\infty, \quad (5.1)\]

the change \(q \to q^{-1}\) (i.e. \(\kappa \to i\kappa\)) in the function \(\rho(\kappa x; a, b, c, d|q)\) appearing in (2.10) and (3.1), transforms it into

\[\rho(i\kappa x; a, b, c, d|q^{-1}) = \prod_{v=a, b, c, d} (ivq e^{\kappa x}, -ivq e^{-\kappa x}, q)_\infty = \prod_{v=a, b, c, d} E_q(ivq e^{\kappa x})E_q(-ivq e^{-\kappa x}), \quad (5.2)\]

where \(E_q(z) = e_q^{-1}(-z) = (-z; q)_\infty\) [2]. Therefore, under the transformation \(q \to q^{-1}\), the orthogonality relation (3.1) for the Askey-Wilson polynomials with the parameter \(q < 1\) converts into the following orthogonality relation for the Askey-Wilson polynomials with \(q > 1\):

\[\int_{-\infty}^{\infty} p_m(i \sinh \kappa x; a, b, c, d|q^{-1}) p_n(i \sinh \kappa x; a, b, c, d|q^{-1}) \rho(i\kappa x; a, b, c, d|q^{-1}) e^{-x^2} \cosh \kappa x dx = \delta_{mn} I_n(a, b, c, d|q^{-1}) \quad (5.3)\]

The explicit form of \(I_n(a, b, c, d|q^{-1})\) is readily obtained from (4.16), upon making use of the formulas (5.1) and \((a; q^{-1})_n = (a^{-1}; q)_n(-a)^n q^{-n(n-1)/2}\) [2].

On the other hand, with the aid of the explicit representation for the Askey-Wilson polynomials [1, 2]

\[p_n(\sin \varphi; a, b, c, d|q) = (ab, ac, ad; q)_n a^{-n} \phi_3 \left[q^{-n}, abcd q^{n-1}, iae^{i\varphi}, -iae^{-i\varphi} \atop ab, ac, ad; q, q\right] \quad (5.4)\]

and the inversion formula (with respect to the transformation \(q \to q^{-1}\)) for the basic hypergeometric series \(\phi_3\) (see [2], p.21, exercise 1.4(i)), it is easy to show that

\[p_n(x; a, b, c, d|q^{-1}) = (-1)^n(abcd)^n q^{-\frac{n^2}{2}} p_n(x; a^{-1}, b^{-1}, c^{-1}, d^{-1}|q). \quad (5.5)\]

Consequently, from (5.3) and (5.5) it follows the orthogonality relation

\[\int_{-\infty}^{\infty} p_m(i \sinh \kappa x; a^{-1}, b^{-1}, c^{-1}, d^{-1}|q)p_n(i \sinh \kappa x; a^{-1}, b^{-1}, c^{-1}, d^{-1}|q)\rho(i\kappa x; a, b, c, d|q^{-1}) \ast e^{-x^2} \cosh \kappa x dx = (q, 1/ab, 1/ac, 1/ad, 1/bc, 1/bd, 1/cd; q)_n \frac{I_0(a, b, c, d|q^{-1})}{(1 - q^{2n-1}/abcd)(1/abcd; q)_{n-1}} \delta_{mn} \quad (5.6)\]

for the Askey-Wilson polynomials with the parameters \(|v| > 1, v = a, b, c, d\) and \(0 < q < 1\). The value of the integral \(I_0(a, b, c, d|q^{-1})\) is simple to obtain from (4.15) by means of the formula (5.1).
6 Concluding remarks.

The orthogonality relations (3.1) and (5.6) are bound to be related by the Fourier transformation for the Askey-Wilson functions, analogous to the well-known transformation for the harmonic oscillator wave functions $H_n(x) \exp(-x^2/2)$ (or Hermite functions in the terminology of mathematicians [15, 16]) connecting the coordinate and momentum realizations in quantum mechanics. It should be interesting to compare this Fourier transformation with the q-transformations, that reproduce the Askey-Wilson polynomials [17, 18]. For the q-Hermite functions $H_n(\sin \kappa x \mid q) \exp(-x^2/2)$, $q = \exp(-2\kappa^2)$, which are the simplest case of the Askey-Wilson functions with vanishing parameters $a, b, c,$ and $d$, such Fourier transformation has the form [5]

$$
\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp(\text{i}xy - x^2/2)\! H_n(\sin \kappa x \mid q) dx = i^n q^{n^2/4} h_n(\sinh \kappa y \mid q) \exp(-y^2/2).
$$

The general case needs to be analyzed in greater detail.

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References


