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**A MULTILINEAR GENERATING FUNCTION FOR THE
KONHAUSER SETS OF BIORTHOGONAL POLYNOMIALS
SUGGESTED BY THE LAGUERRE POLYNOMIALS**

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H. M. SRIVASTAVA

The polynomial sets $\{Y_n^\alpha(x; k)\}$ and $\{Z_n^\alpha(x; k)\}$, discussed by Joseph D. E. Konhauser, are biorthogonal over the interval $(0, \infty)$ with respect to the weight function $x^\alpha e^{-x}$, where $\alpha > -1$ and k is a positive integer. The object of the present note is to develop a fairly elementary method of proving a general multilinear generating function which, upon suitable specializations, yields a number of interesting results including, for example, a multivariable hypergeometric generating function for the multiple sum:

$$\begin{aligned}
 (*) \quad & \sum_{n_1, \dots, n_r=0}^{\infty} (m + n_1 + \dots + n_r)! Y_{m+n_1+\dots+n_r}^\alpha(x; k) \\
 & \cdot \prod_{i=1}^r \left\{ \frac{Z_{n_i}^{\beta_i}(y_i; s_i) u_i^{n_i}}{(1 + \beta_i)_{s_i, n_i}} \right\},
 \end{aligned}$$

involving the Konhauser biorthogonal polynomials; here, by definition,

$$\alpha > -1; \quad \beta_i > -1; \quad k, s_i = 1, 2, 3, \dots; \quad \forall i \in \{1, \dots, r\}.$$

1. Introduction. Joseph D. E. Konhauser ([5]; see also [4]) introduced two interesting classes of polynomials: $Y_n^\alpha(x; k)$ a polynomial in x , and $Z_n^\alpha(x; k)$ a polynomial in x^k , $\alpha > -1$ and $k = 1, 2, 3, \dots$. For $k = 1$, these polynomials reduce to the classical Laguerre polynomials $L_n^{(\alpha)}(x)$, and for $k = 2$ they were encountered earlier by Spencer and Fano [8] in the study of the penetration of gamma rays through matter and were discussed subsequently by Preiser [7]. Also [5, p. 303]

$$\begin{aligned}
 (1) \quad & \int_0^\infty x^\alpha e^{-x} Y_m^\alpha(x; k) Z_n^\alpha(x; k) dx \\
 & = \frac{\Gamma(kn + \alpha + 1)}{n!} \delta_{mn}, \quad \forall m, n \in \{0, 1, 2, \dots\},
 \end{aligned}$$

so that the Konhauser polynomial sets $\{Y_n^\alpha(x; k)\}$ and $\{Z_n^\alpha(x; k)\}$ are *biorthogonal* over the interval $(0, \infty)$ with respect to the weight function $x^\alpha e^{-x}$, where $\alpha > -1$, k is a positive integer, and δ_{mn} is the Kronecker delta.

The following explicit expression for the polynomials $Z_n^\alpha(x; k)$ was given by Konhauser [5, p. 304, Eq. (5)]:

$$(2) \quad Z_n^\alpha(x; k) = \frac{\Gamma(kn + \alpha + 1)}{n!} \sum_{j=0}^n (-1)^j \binom{n}{j} \frac{x^{kj}}{\Gamma(kj + \alpha + 1)}.$$

Subsequently, Carlitz pointed out that [2, p. 427, Eq. (9)]

$$(3) \quad Y_n^\alpha(x; k) = \frac{1}{n!} \sum_{j=0}^n \frac{x^j}{j!} \sum_{l=0}^j (-1)^l \binom{j}{l} \left(\frac{l + \alpha + 1}{k} \right)_n,$$

where $(\lambda)_n = \Gamma(\lambda + n)/\Gamma(\lambda)$.

In a recent paper [10] we derived various properties of (for example) the Konhauser biorthogonal polynomials $Y_n^\alpha(x; k)$ by suitably specializing those of the Srivastava-Singhal polynomials $G_n^{(\alpha)}(x, h, p, k)$ which are defined by the generalized Rodrigues formula [14, p. 75, Eq. (1.3)]

$$(4) \quad G_n^{(\alpha)}(x, h, p, k) = \frac{x^{-kn-\alpha} \exp(px^h)}{n!} \cdot (x^{k+1} D_x)^n \{ x^\alpha \exp(-px^h) \}, \quad D_x = \frac{d}{dx},$$

and given explicitly by [14, p. 77, Eq. (2.1)]

$$(5) \quad G_n^{(\alpha)}(x, h, p, k) = \frac{k^n}{n!} \sum_{j=0}^n \frac{(px^h)^j}{j!} \sum_{l=0}^j (-1)^l \binom{j}{l} \left(\frac{hl + \alpha}{k} \right)_n,$$

where the parameters α, h, k and p are unrestricted, in general. In fact, by comparing (5) with Carlitz's result (3), we at once deduce the known relationship [13, p. 315, Eq. (83)]

$$(6) \quad Y_n^\alpha(x; k) = k^{-n} G_n^{(\alpha+1)}(x, 1, 1, k), \quad \alpha > -1; k = 1, 2, 3, \dots,$$

which was of fundamental importance in our paper [10].

The object of the present note is first to give a rather elementary proof of a general multilinear generating function for the Srivastava-Singhal polynomials $G_n^{(\alpha)}(x, h, p, k)$. We then show how this multilinear generating function can be further generalized and applied to derive a

number of interesting results including, for example, a multivariable hypergeometric generating function for the multiple sum (*) involving the product of several Konhauser biorthogonal polynomials. Our main result is contained in the following

THEOREM. *For a bounded multiple sequence $\{\Lambda(n_1, \dots, n_r)\}$ of arbitrary complex numbers, let*

$$(7) \quad \mathcal{H}[n_1, \dots, n_r; y_1, \dots, y_r] = \sum_{j_1=0}^{[n_1/m_1]} \dots \sum_{j_r=0}^{[n_r/m_r]} \frac{(-n_1)_{m_1 j_1}}{j_1!} \dots \frac{(-n_r)_{m_r j_r}}{j_r!} \cdot \Lambda(j_1, \dots, j_r) y_1^{j_1} \dots y_r^{j_r},$$

where m_1, \dots, m_r are positive integers. Also let Δ_r be defined by

$$(8) \quad \Delta_r = 1 - \sum_{i=1}^r u_i, \quad r = 1, 2, 3, \dots$$

Then, for every nonnegative integer m ,

$$(9) \quad \sum_{n_1, \dots, n_r=0}^{\infty} (m + n_1 + \dots + n_r)! G_{m+n_1+\dots+n_r}^{(\alpha)}(x, h, p, k) \cdot \mathcal{H}[n_1, \dots, n_r; y_1, \dots, y_r] \frac{(u_1/k)^{n_1}}{n_1!} \dots \frac{(u_r/k)^{n_r}}{n_r!} = k^m \exp(px^h) \Delta_r^{-m-\alpha/k} \cdot \sum_{n, n_1, \dots, n_r=0}^{\infty} \left(\frac{hn + \alpha}{k}\right)_{m+m_1 n_1 + \dots + m_r n_r} \left(\frac{1}{n!}\right) \Lambda(n_1, \dots, n_r) \left(-\frac{px^h}{\Delta_r^{h/k}}\right)^n \cdot \prod_{i=1}^r \left\{ \frac{[(-u_i/\Delta_r)^{m_i} y_i]^{n_i}}{n_i!} \right\}, \quad k \neq 0,$$

provided that the multiple series on the right-hand side of (9) has a meaning, and

$$(10) \quad |u_1 + \dots + u_r| < 1.$$

2. Proof of the theorem. For convenience, let $\Omega(u_1, \dots, u_r)$ denote the left-hand side of (9), and set

$$(11) \quad N = n_1 + \dots + n_r \quad \text{and} \quad J = m_1 j_1 + \dots + m_r j_r.$$

Applying the explicit representation (5) and the definition (7), we find that

$$\begin{aligned}
 (12) \quad \Omega(u_1, \dots, u_r) &= k^m \sum_{n_1, \dots, n_r=0}^{\infty} u_1^{n_1} \cdots u_r^{n_r} \\
 &\cdot \sum_{j=0}^{m+N} \frac{(px^h)^j}{j!} \sum_{l=0}^j (-1)^l \binom{j}{l} \left(\frac{hl + \alpha}{k} \right)_{m+N} \\
 &\cdot \prod_{i=1}^r \left\{ \sum_{j_i=0}^{[n_i/m_i]} \frac{[(-1)^{m_i} y_i]^{j_i}}{j_i! (n_i - m_i j_i)!} \right\} \Lambda(j_1, \dots, j_r) \\
 &= k^m \sum_{j_1, \dots, j_r=0}^{\infty} \Lambda(j_1, \dots, j_r) \prod_{i=1}^r \left\{ \frac{[(-u_i)^{m_i} y_i]^{j_i}}{j_i!} \right\} \\
 &\cdot \sum_{n_1, \dots, n_r=0}^{\infty} \frac{u_1^{n_1}}{n_1!} \cdots \frac{u_r^{n_r}}{n_r!} \sum_{j=0}^{m+N+J} \frac{(px^h)^j}{j!} \\
 &\cdot \sum_{l=0}^j (-1)^l \binom{j}{l} \left(\frac{hl + \alpha}{k} \right)_{m+N+J}.
 \end{aligned}$$

Now we appeal to the series identity [9, p. 4, Eq. (12)]

$$\begin{aligned}
 (13) \quad \sum_{n_1, \dots, n_r=0}^{\infty} f(n_1 + \cdots + n_r) \frac{u_1^{n_1}}{n_1!} \cdots \frac{u_r^{n_r}}{n_r!} \\
 = \sum_{n=0}^{\infty} f(n) \frac{(u_1 + \cdots + u_r)^n}{n!},
 \end{aligned}$$

and (12) becomes

$$\begin{aligned}
 (14) \quad \Omega(u_1, \dots, u_r) &= k^m \sum_{n, j_1, \dots, j_r=0}^{\infty} \frac{(u_1 + \cdots + u_r)^n}{n!} \\
 &\cdot \prod_{i=1}^r \left\{ \frac{[(-u_i)^{m_i} y_i]^{j_i}}{j_i!} \right\} \sum_{j=0}^{m+n+J} \frac{(px^h)^j}{j!} \\
 &\cdot \sum_{l=0}^j (-1)^l \binom{j}{l} \left(\frac{hl + \alpha}{k} \right)_{m+n+J},
 \end{aligned}$$

where J is defined, as before, by (11).

The innermost sum in (14) is the j th difference of a polynomial of degree $m + n + J$ in α ; it is nil when $j > m + n + J$. Thus we have

$$\begin{aligned} & \sum_{j=0}^{m+n+J} \frac{(px^h)^j}{j!} \sum_{l=0}^j (-1)^l \binom{j}{l} \left(\frac{hl + \alpha}{k}\right)_{m+n+J} \\ &= \sum_{l=0}^{\infty} \left(\frac{hl + \alpha}{k}\right)_{m+n+J} \frac{(-px^h)^l}{l!} \sum_{j=0}^{\infty} \frac{(px^h)^j}{j!} \\ &= \exp(px^h) \sum_{l=0}^{\infty} \left(\frac{hl + \alpha}{k}\right)_{m+n+J} \frac{(-px^h)^l}{l!}, \end{aligned}$$

and substituting this expression in (14), and applying the binomial expansion to sum the resulting n -series, we finally obtain

$$\begin{aligned} (15) \quad \Omega(u_1, \dots, u_r) &= k^m \exp(px^h) \Delta_r^{-m-\alpha/k} \\ &\cdot \sum_{l, j_1, \dots, j_r=0}^{\infty} \left(\frac{hl + \alpha}{k}\right)_{m+J} \binom{l}{l!} \Lambda(j_1, \dots, j_r) \left(-\frac{px^h}{\Delta_r^{h/k}}\right)^l \\ &\cdot \prod_{i=1}^r \left\{ \frac{[(-u_i/\Delta_r)^{m_i} y_i]^{j_i}}{j_i!} \right\}, \quad k \neq 0, \end{aligned}$$

where Δ_r and J are given by (8) and (11), respectively, and the inequality in (10) is assumed to hold.

The right-hand sides of (9) and (15) are essentially the same. This evidently completes the proof of our theorem under the hypothesis that the various interchanges of the order of summation are permissible by absolute convergence of the series involved. Thus, in general, our theorem holds true whenever each member of (9) has a meaning.

REMARK. Our method of derivation can be applied *mutatis mutandis* in order to prove the following generalization of the multilinear generating function (9):

$$\begin{aligned} (16) \quad & \sum_{n_1, \dots, n_r=0}^{\infty} (m + n_1 + \dots + n_r)! \mathcal{F}_{m+n_1+\dots+n_r}^{(\alpha)}(x, h, p, k) \\ & \cdot \mathcal{H}[n_1, \dots, n_r; y_1, \dots, y_r] \frac{(u_1/k)^{n_1}}{n_1!} \dots \frac{(u_r/k)^{n_r}}{n_r!} \\ &= k^m \exp(px^h) \Delta_r^{-m-\alpha/k} \sum_{n, n_1, \dots, n_r=0}^{\infty} \left(\frac{hn + \alpha}{k}\right)_{m+m_1 n_1 + \dots + m_r n_r} \\ & \cdot \frac{\xi_n}{n!} \Delta(n_1, \dots, n_r) \left(-\frac{px^h}{\Delta_r^{h/k}}\right)^n \prod_{i=1}^r \left\{ \frac{[(-u_i/\Delta_r)^{m_i} y_i]^{n_i}}{n_i!} \right\}, \quad k \neq 0, \end{aligned}$$

where, in terms of the bounded sequence $\{\xi_n\}$ of arbitrary complex numbers,

$$(17) \quad \mathcal{F}_n^{(\alpha)}(x, h, p, k) = \frac{k^n}{n!} \sum_{j=0}^{\infty} \frac{(px^h)^j}{j!} \sum_{l=0}^j (-1)^l \binom{j}{l} \xi_l \left(\frac{hl + \alpha}{k} \right)_n,$$

which obviously reduces to the Srivastava-Singhal equation (5) when $\xi_l = 1, l \geq 0$.

3. Applications. By assigning suitable special values to the arbitrary coefficients $\Lambda(j_1, \dots, j_r)$, the multiple sum in (7) can indeed be expressed in terms of the generalized Lauricella hypergeometric function of r variables [11, p. 454]. Thus, following the various notations and conventions explained fairly fully by Srivastava and Daoust ([11, p. 545 *et seq.*]; see also [12]), we obtain from our theorem the multivariable hypergeometric generating function:

$$(18) \quad \sum_{n_1, \dots, n_r=0}^{\infty} (m + n_1 + \dots + n_r)! G_{m+n_1+\dots+n_r}^{(\alpha)}(x, h, p, k) \\ \cdot {}_F^A : 1 + B'; \dots; 1 + B^{(r)} \left(\begin{matrix} [(a) : \theta', \dots, \theta^{(r)}] : [-n_1 : m_1], & [(b') : \phi']; \dots; \\ C : D'; \dots; D^{(r)} & \left[[(c) : \psi', \dots, \psi^{(r)}] : \right. & [(d') : \delta']; \dots; \\ & \left. [-n_r : m_r], [(b^{(r)}) : \phi^{(r)}] ; \right. & \left. \left[(d^{(r)}) : \delta^{(r)}] ; y_1, \dots, y_r \right] \left(\frac{u_1}{k} \right)^{n_1} \dots \left(\frac{u_r}{k} \right)^{n_r} \right) \\ = k^m \left(\frac{\alpha}{k} \right)_m \exp(px^h) \Delta_r^{-m-\alpha/k} F^{1+A:0; B'; \dots; B^{(r)}} \\ C:1; D'; \dots; D^{(r)} \\ \left(\begin{matrix} [m + \alpha/k : h/k, m_1, \dots, m_r], [(a) : 0, \theta', \dots, \theta^{(r)}] : \text{---} ; \\ [(c) : 0, \psi', \dots, \psi^{(r)}] : [\alpha/k : h/k] ; \\ [(b') : \phi']; \dots; [(b^{(r)}) : \phi^{(r)}] ; \Xi_0, \Xi_1, \dots, \Xi_r \end{matrix} \right), \quad k \neq 0, \\ [(d') : \delta']; \dots; [(d^{(r)}) : \delta^{(r)}] ; \end{matrix}$$

where $h/k > 0, \Delta_r$ is given by (8), and

$$(19) \quad \Xi_0 = -\frac{px^h}{\Delta_r^{h/k}}, \quad \Xi_i = y_i \left(-\frac{u_i}{\Delta_r} \right)^{m_i}, \quad i = 1, \dots, r.$$

Next we set $A = C = 0$ in (18) and, for convenience, let each of the positive coefficients $\phi_j^{(i)}, j = 1, \dots, B^{(i)}; \delta_j^{(i)}, j = 1, \dots, D^{(i)}$ ($i = 1, \dots, r$) equal 1. Denoting the array of parameters

$$(-n_i + j - 1)/m_i, \quad j = 1, \dots, m_i,$$

by $\Delta(m_i; -n_i), i = 1, \dots, r$, we thus find from (18) that

$$\begin{aligned}
 (20) \quad & \sum_{n_1, \dots, n_r=0}^{\infty} (m+n_1+\dots+n_r)! G_{m+n_1+\dots+n_r}^{(\alpha)}(x, h, p, k) \\
 & \cdot \prod_{i=1}^r \left\{ {}_{m_i+B^{(i)}} F_{D^{(i)}} \left[\begin{matrix} \Delta(m_i; -n_i), & (b^{(i)}); \\ & (d^{(i)}); \end{matrix} y_i m_i^{n_i} \right] \left(\frac{u_i}{k} \right)^{n_i} \right\} \\
 & = k^m \left(\frac{\alpha}{k} \right)_m \exp(px^h) \Delta_r^{-m-\alpha/k} \\
 & \cdot F \begin{matrix} 1 : 0; B'; \dots; B^{(r)} \\ 0 : 1; D'; \dots; D^{(r)} \end{matrix} \left(\begin{matrix} [m + \alpha/k : h/k, m_1, \dots, m_r] : \text{---} \\ \text{---} : [\alpha/k : h/k]; \\ [(b^{(r)} : 1); \dots; [(b^{(1)} : 1)]; \\ [(d^{(r)} : 1); \dots; [(d^{(1)} : 1)]; \Xi_0, \Xi_1, \dots, \Xi_r \end{matrix} \right), \quad k \neq 0,
 \end{aligned}$$

where $h/k > 0$, Δ_r is given by (8), and $\Xi_0, \Xi_1, \dots, \Xi_r$ are defined by (19).

Obviously, this last formula (20) generates the product of r generalized hypergeometric polynomials; it is a generalization of several known results due to Srivastava and Singhal [15].

For special values of the parameters, the Srivastava-Singhal polynomials $G_n^{(\alpha)}(x, h, p, k)$ can be reduced to the classical Hermite and Laguerre polynomials and their various generalizations studied in the literature (*cf.* [14, p. 76]). Furthermore, the generalized hypergeometric polynomials occurring in (20) can be specialized to several important classes of hypergeometric polynomials including, for example, the classical Hermite polynomials and their such generalizations as those considered by Gould and Hopper [3, p. 58]

$$\begin{aligned}
 (21) \quad & g_n^m(x, \lambda) = \sum_{j=0}^{[n/m]} \frac{n!}{j!(n-mj)!} \lambda^j x^{n-mj} \\
 & = x^n {}_m F_0 \left[\begin{matrix} \Delta(m; -n); \\ \text{---}; \end{matrix} \lambda \left(-\frac{m}{x} \right)^m \right],
 \end{aligned}$$

and by Brafman [1, p. 186]

$$\begin{aligned}
 (22) \quad & \mathcal{B}_n^m [\alpha_1, \dots, \alpha_r; \beta_1, \dots, \beta_s; x] \\
 & = {}_{m+r} F_s \left[\begin{matrix} \Delta(m; -n), & \alpha_1, \dots, \alpha_r; \\ & \beta_1, \dots, \beta_s; \end{matrix} x \right],
 \end{aligned}$$

where, as in (20), $\Delta(m; -n)$ abbreviates the array of m parameters

$$(-n + j - 1)/m, \quad j = 1, \dots, m,$$

m being an arbitrary positive integer. The details involved in these derivations of known or new multilinear generating functions from (20) may be left as an exercise to the interested reader.

Yet another interesting application of our theorem would result when in (18) we set

$$\begin{cases} h = p = 1, & A = B^{(i)} = C = D^{(i)} - 1 = 0, \\ d_1^{(i)} = 1 + \beta_i, & \delta_1^{(i)} = s_i, \quad m_i = 1, \quad i = 1, \dots, r, \end{cases}$$

replace α by $\alpha + 1$, and y_i by $y_i^{s_i}$, $i = 1, \dots, r$, and appeal to the relationship (6) and to the explicit representation (2). We thus obtain our desired multilinear generating function for the Konhauser biorthogonal polynomials in the form:

$$\begin{aligned} (23) \quad & \sum_{n_1, \dots, n_r=0}^{\infty} (m + n_1 + \dots + n_r)! Y_{m+n_1+\dots+n_r}^{\alpha}(x; k) \\ & \cdot \prod_{i=1}^r \left\{ Z_{n_i}^{\beta_i}(y_i; s_i) \frac{u_i^{n_i}}{(1 + \beta_i)_{s_i n_i}} \right\} \\ & = \left(\frac{\alpha + 1}{k} \right)_m e^{x \Delta_r^{-m-(\alpha+1)/k}} \\ & \cdot F \begin{matrix} 1; 0; \dots; 0 \\ 0; 1; \dots; 1 \end{matrix} \left(\begin{matrix} [m + (\alpha + 1)/k : 1/k, 1, \dots, 1] : \\ \hline [(\alpha + 1)/k : 1/k]; \quad [1 + \beta_1 : s_1]; \quad \dots; \\ \hline [1 + \beta_r : s_r]; \quad -\frac{x}{\Delta_r^{1/k}}, -\frac{u_1 y_1^{s_1}}{\Delta_r}, \dots, -\frac{u_r y_r^{s_r}}{\Delta_r} \end{matrix} \right), \end{aligned}$$

where, by definition,

$$(24) \quad \alpha > -1; \quad \beta_i > -1; \quad k, s_i = 1, 2, 3, \dots; \quad \forall i \in \{1, \dots, r\}.$$

A seriously erroneous version of a *special* case of the multilinear generating function (23), when $s_1 = \dots = s_r = s$, was proven earlier by Patil and Thakare [6] who incidentally used a markedly different method. In fact, (23) with $k = s_1 = \dots = s_r = 1$ is a well-known result (involving the classical Laguerre polynomials) due to Srivastava and Singhal [15, p. 1239, Eq. (5)].

Since s_1, \dots, s_r are, by definition, positive integers, the multilinear generating function (23) would follow also as an obvious special case of (20).

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