

## RECURRENCE RELATIONS FOR THE MOMENTS OF DISCRETE SEMICLASSICAL ORTHOGONAL POLYNOMIALS

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*Abstract.* We study recurrence relations satisfied by the moments  $v_n(z)$  of a linear functional  $L$  whose first moment satisfies a differential equation (in  $z$ ) with polynomial coefficients.

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### REFERENCES

- [1] F. ABDELKARIM AND P. MARONI, *The  $D_\omega$ -classical orthogonal polynomials*, Results Math. **32** (1–2), 1–28 (1997).
- [2] N. I. AHEIZER AND M. KREIN, *Some questions in the theory of moments*, Translations of Mathematical Monographs, Vol. 2, American Mathematical Society, Providence, R.I. (1962).
- [3] N. I. AKHIEZER, *The classical moment problem and some related questions in analysis*, Translated by N. Kemmer. Hafner Publishing Co., New York (1965).
- [4] M. ALFARO, F. MARCELLÁN, A. PEÑA, AND M. L. REZOLA, *On linearly related orthogonal polynomials and their functionals*, J. Math. Anal. Appl. **287** (1), 307–319 (2003).
- [5] R. ÁLVAREZ NODARSE, J. ARVESÚ, AND F. MARCELLÁN, *Modifications of quasi-definite linear functionals via addition of delta and derivatives of delta Dirac functions*, Indag. Math. (N.S.) **15** (1), 1–20 (2004).
- [6] R. ÁLVAREZ NODARSE AND J. PETRONILHO, *On the Krall-type discrete polynomials*, J. Math. Anal. Appl. **295** (1), 55–69 (2004).
- [7] R. ÁLVAREZ NODARSE, J. PETRONILHO, N. C. PINZÓN-CORTÉS, AND R. SEVINIK-ADI GÜZEL, *On linearly related sequences of difference derivatives of discrete orthogonal polynomials*, J. Comput. Appl. Math. **284**, 26–37 (2015).
- [8] G. E. ANDREWS, R. ASKEY, AND R. ROY, *Special functions*, vol. 71 of Encyclopedia of Mathematics and its Applications, Cambridge University Press, Cambridge (1999).
- [9] A. I. APTEKAREV, A. BRANQUINHO, AND F. MARCELLÁN, *Toda-type differential equations for the recurrence coefficients of orthogonal polynomials and Freud transformation*, J. Comput. Appl. Math. **78** (1), 139–160 (1997).
- [10] R. ASKEY, *Orthogonal polynomials and special functions*, Society for Industrial and Applied Mathematics, Philadelphia, Pa. (1975).
- [11] C. F. BRACCIALI, T. E. PÉREZ, M. A. PIÑAR, AND M. A. PIÑAR, *Stieltjes functions and discrete classical orthogonal polynomials*, Comput. Appl. Math. **32** (3), 537–547 (2013).
- [12] M. I. BUENO AND F. M. DOPICO, *A more accurate algorithm for computing the Christoffel transformation*, J. Comput. Appl. Math. **205** (1), 567–582 (2007).
- [13] M. I. BUENO AND F. MARCELLÁN, *Darboux transformation and perturbation of linear functionals*, Linear Algebra Appl. **384**, 215–242 (2004).
- [14] T. S. CHIHARA, *An introduction to orthogonal polynomials*, Gordon and Breach Science Publishers, New York-London-Paris (1978).
- [15] T. S. CHIHARA, *Orthogonal polynomials and measures with end point masses*, Rocky Mountain J. Math. **15** (3), 705–719 (1985).
- [16] E. B. CHRISTOFFEL, *Über die Gaußische Quadratur und eine Verallgemeinerung derselben*, J. Reine Angew. Math. **55**, 61–82 (1858).

- [17] F. A. COSTABILE, M. I. GUALTIERI, AND A. NAPOLI, *Matrix calculus-based approach to orthogonal polynomial sequences*, *Mediterr. J. Math.* **17** (4), Paper No. 118, 22 (2020).
- [18] P. J. DAVIS, *Interpolation and approximation*, Dover Publications, Inc., New York (1975).
- [19] M. DEREVYAGIN, J. C. GARCÍA-ARDILA, AND F. MARCELLÁN, *Multiple Geronimus transformations*, *Linear Algebra Appl.* **454**, 158–183 (2014).
- [20] M. DEREVYAGIN AND F. MARCELLÁN, *A note on the Geronimus transformation and Sobolev orthogonal polynomials*, *Numer. Algorithms* **67** (2), 271–287 (2014).
- [21] D. DOMINICI, *Polynomial sequences associated with the moments of hypergeometric weights*, *SIGMA Symmetry Integrability Geom. Methods Appl.* **12**, Paper No. 044, 18 (2016).
- [22] D. DOMINICI, *Matrix factorizations and orthogonal polynomials*, *Random Matrices Theory Appl.* **9** (1), 2040003, 33 (2020).
- [23] D. DOMINICI, *Recurrence coefficients of Toda-type orthogonal polynomials I. Asymptotic analysis*, *Bull. Math. Sci.* **10** (2), 2050003, 32 (2020).
- [24] D. DOMINICI AND F. MARCELLÁN, *Discrete semiclassical orthogonal polynomials of class one*, *Pacific J. Math.* **268** (2), 389–411 (2014).
- [25] D. DOMINICI AND F. MARCELLÁN, *Discrete semiclassical orthogonal polynomials of class 2*, in *Orthogonal polynomials: current trends and applications*, vol. 22 of SEMA SIMAI Springer Ser., pp. 103–169. Springer, Cham ([2021] ©2021).
- [26] D. DOMINICI AND V. PILLWEIN, *Difference equation satisfied by the Stieltjes transform of a sequence*, *DK-Report*, Johannes Kepler University Linz **2018-11**, 17 pp. (2018).
- [27] A. J. DURÁN, *Orthogonal polynomials satisfying higher-order difference equations*, *Constr. Approx.* **36** (3), 459–486 (2012).
- [28] A. J. DURÁN, *Christoffel transform of classical discrete measures and invariance of determinants of classical and classical discrete polynomials*, *J. Math. Anal. Appl.* **503** (2), Paper No. 125306, 29 (2021).
- [29] G. FREUD, *Orthogonale Polynome*, *Lehrbücher und Monographien aus dem Gebiete der Exakten Wissenschaften, Mathematische Reihe, Band 33*, Birkhäuser Verlag, Basel-Stuttgart (1969).
- [30] L. G. GARZA, L. E. GARZA, F. MARCELLÁN, AND N. C. PINZÓN-CORTÉS, *A matrix characterization for the  $D_V$ -semiclassical and  $D_V$ -coherent orthogonal polynomials*, *Linear Algebra Appl.* **487**, 242–259 (2015).
- [31] W. GAUTSCHI, *Orthogonal polynomials: computation and approximation*, *Numerical Mathematics and Scientific Computation*, Oxford University Press, New York (2004).
- [32] J. GERONIMUS, *On polynomials orthogonal with regard to a given sequence of numbers*, *Comm. Inst. Sci. Math. Méc. Univ. Kharkoff [Zapiski Inst. Mat. Mech.]* (4) **17**, 3–18 (1940).
- [33] M. E. H. ISMAIL, *Classical and quantum orthogonal polynomials in one variable*, vol. 98 of *Encyclopedia of Mathematics and its Applications*, Cambridge University Press, Cambridge (2005).
- [34] M. E. H. ISMAIL AND D. STANTON, *Classical orthogonal polynomials as moments*, *Canad. J. Math.* **49** (3), 520–542 (1997).
- [35] M. E. H. ISMAIL AND D. STANTON, *More orthogonal polynomials as moments*, in *Mathematical essays in honor of Gian-Carlo Rota* (Cambridge, MA, 1996), vol. 161 of *Progr. Math.*, pp. 377–396, Birkhäuser Boston, Boston, MA (1998).
- [36] M. E. H. ISMAIL AND D. STANTON,  *$q$ -integral and moment representations for  $q$ -orthogonal polynomials*, *Canad. J. Math.* **54** (4), 709–735 (2002).
- [37] C. JORDAN, *Calculus of finite differences*, Chelsea Publishing Co., New York, third ed. (1965).
- [38] L. KHERIJ, *An introduction to the  $H_q$ -semiclassical orthogonal polynomials*, *Methods Appl. Anal.* **10** (3), 387–411 (2003).
- [39] D. H. KIM, K. H. KWON, AND S. B. PARK, *Delta perturbation of a moment functional*, *Appl. Anal.* **74** (3–4), 463–477 (2000).
- [40] R. KOEKOEK, P. A. LESKY, AND R. F. SWARTTOUW, *Hypergeometric orthogonal polynomials and their  $q$ -analogues*, *Springer Monographs in Mathematics*, Springer-Verlag, Berlin (2010).
- [41] J. H. LEE AND K. H. KWON, *Division problem of moment functionals*, vol. 32, pp. 739–758, (2002), *Conference on Special Functions* (Tempe, AZ, 2000).
- [42] A. M. LEGENDRE, *Recherches sur l'attraction des sphéroïdes homogènes*, *Mémoires de Mathématiques et de Physique, présentés à l'Académie Royale des Sciences, par divers savans, et lus dans ses Assemblées* **Tom X**, 411–435 (1785).

- [43] M. MAÑAS, *Pearson equations for discrete orthogonal polynomials: III—Christoffel and Geronimus transformations*, Rev. R. Acad. Cienc. Exactas Fís. Nat. Ser. A Mat. RACSAM **116** (4), Paper No. 168, 23 (2022).
- [44] M. MAÑAS, I. FERNÁNDEZ-IRISARRI, AND O. F. GONZÁLEZ-HERNÁNDEZ, *Pearson Equations for Discrete Orthogonal Polynomials: I. Generalized Hypergeometric Functions and Toda Equations*, [arXiv:2107.01747](https://arxiv.org/abs/2107.01747) (2021).
- [45] M. MAÑAS, I. FERNÁNDEZ-IRISARRI, AND O. F. GONZÁLEZ-HERNÁNDEZ, *Pearson equations for discrete orthogonal polynomials: I. Generalized hypergeometric functions and Toda equations*, Stud. Appl. Math. **148** (3), 1141–1179 (2022).
- [46] I. G. MACDONALD, *Symmetric functions and Hall polynomials*, Oxford Classic Texts in the Physical Sciences, The Clarendon Press, Oxford University Press, New York, second ed. (2015).
- [47] A. P. MAGNUS, *Painlevé-type differential equations for the recurrence coefficients of semi-classical orthogonal polynomials*, in *Proceedings of the Fourth International Symposium on Orthogonal Polynomials and their Applications* (Evian-Les-Bains, 1992), vol. 57, pp. 215–237 (1995).
- [48] F. MARCELLÁN, H. CHAGGARA, AND N. AYADI, *2-Orthogonal polynomials and Darboux transformations. Applications to the discrete Hahn-classical case*, J. Difference Equ. Appl. **27** (3), 431–452 (2021).
- [49] F. MARCELLÁN AND P. MARONI, *Sur l’adjonction d’une masse de Dirac à une forme régulière et semi-classique*, Ann. Mat. Pura Appl. (4) **162**, 1–22 (1992).
- [50] F. MARCELLÁN AND L. SALTO, *Discrete semi-classical orthogonal polynomials*, J. Differ. Equations Appl. **4** (5), 463–496 (1998).
- [51] P. MARONI, *Une caractérisation des polynômes orthogonaux semi-classiques*, C. R. Acad. Sci. Paris Sér. I Math. **301** (6), 269–272 (1985).
- [52] P. MARONI, *Prolégomènes à l’étude des polynômes orthogonaux semi-classiques*, Ann. Mat. Pura Appl. (4) **149**, 165–184 (1987).
- [53] P. MARONI, *Le calcul des formes linéaires et les polynômes orthogonaux semi-classiques*, in *Orthogonal polynomials and their applications (Segovia, 1986)*, vol. 1329 of Lecture Notes in Math., pp. 279–290. Springer, Berlin (1988).
- [54] P. MARONI, *Sur la suite de polynômes orthogonaux associée à la forme  $u = \delta_c + \lambda(x-c)^{-1}L$* , Period. Math. Hungar. **21** (3), 223–248 (1990).
- [55] P. MARONI, *Une théorie algébrique des polynômes orthogonaux. Application aux polynômes orthogonaux semi-classiques*, in *Orthogonal polynomials and their applications* (Erice, 1990), vol. 9 of IMACS Ann. Comput. Appl. Math., pp. 95–130. Baltzer, Basel (1991).
- [56] P. MARONI, *Semi-classical character and finite-type relations between polynomial sequences*, Appl. Numer. Math. **31** (3), 295–330 (1999).
- [57] J. C. MEDEM, R. ÁLVAREZ NODARSE, AND F. MARCELLÁN, *On the  $q$ -polynomials: a distributional study*, J. Comput. Appl. Math. **135** (2), 157–196 (2001).
- [58] A. F. NIKIFOROV, S. K. SUSLOV, AND V. B. UVAROV, *Classical orthogonal polynomials of a discrete variable*, Springer Series in Computational Physics, Springer-Verlag, Berlin (1991).
- [59] F. W. J. OLVER, D. W. LOZIER, R. F. BOISVERT, AND C. W. CLARK, editors, *NIST handbook of mathematical functions*, U.S. Department of Commerce, National Institute of Standards and Technology, Washington, DC; Cambridge University Press, Cambridge (2010).
- [60] K. PEARSON, *Contributions to the Mathematical Theory of Evolution. II. skew Variation in Homogeneous Material*, Philos. Trans. Roy. Soc. London Ser. A **186**, 343–414 (1895).
- [61] F. PEHERSTORFER, *Finite perturbations of orthogonal polynomials*, J. Comput. Appl. Math. **44** (3), 275–302 (1992).
- [62] F. PEHERSTORFER, *On Toda lattices and orthogonal polynomials*, in *Proceedings of the Fifth International Symposium on Orthogonal Polynomials, Special Functions and their Applications* (Patras, 1999), vol. 133, pp. 519–534 (2001).
- [63] L. POCHHAMMER, *Ueber hypergeometrische Functionen nter Ordnung*, J. Reine Angew. Math. **71**, 316–352 (1870).
- [64] J. QUAINANCE AND H. W. GOULD, *Combinatorial identities for Stirling numbers*, World Scientific Publishing Co. Pte. Ltd., Singapore (2016).
- [65] S. ROMAN, *The umbral calculus*, vol. 111 of Pure and Applied Mathematics, Academic Press, Inc. [Harcourt Brace Jovanovich, Publishers], New York (1984).

- [66] A. RONVEAUX AND L. SALTO, *Discrete orthogonal polynomials – polynomial modification of a classical functional*, J. Differ. Equations Appl. **7** (3), 323–344 (2001).
- [67] J. A. SHOHAT, *A differential equation for orthogonal polynomials*, Duke Math. J. **5** (2), 401–417 (1939).
- [68] J. A. SHOHAT AND J. D. TAMARKIN, *The Problem of Moments*, American Mathematical Society Mathematical surveys, vol. I. American Mathematical Society, New York (1943).
- [69] L. J. SLATER, *Confluent hypergeometric functions*, Cambridge University Press, New York (1960).
- [70] H. STAHL AND V. TOTIK, *General orthogonal polynomials*, vol. 43 of Encyclopedia of Mathematics and its Applications, Cambridge University Press, Cambridge (1992).
- [71] T. J. STIELTJES, *Œuvres complètes/Collected papers, Vol. I, II*, Springer-Verlag, Berlin (1993).
- [72] M. TODA, *Theory of nonlinear lattices*, vol. 20 of Springer Series in Solid-State Sciences, Springer-Verlag, Berlin-New York (1981).
- [73] V. B. UVAROV, *The connection between systems of polynomials that are orthogonal with respect to different distribution functions*, Ž. Vyčisl. Mat i Mat. Fiz. **9**, 1253–1262 (1969).
- [74] L. VERDE-STAR, *Characterization and construction of classical orthogonal polynomials using a matrix approach*, Linear Algebra Appl. **438** (9), 3635–3648 (2013).
- [75] L. VERDE-STAR, *Recurrence coefficients and difference equations of classical discrete orthogonal and  $q$ -orthogonal polynomial sequences*, Linear Algebra Appl. **440**, 293–306 (2014).
- [76] L. VERDE-STAR, *A unified construction of all the hypergeometric and basic hypergeometric families of orthogonal polynomial sequences*, Linear Algebra Appl. **627**, 242–274 (2021).
- [77] L. VERDE-STAR, *Infinite matrices in the theory of orthogonal polynomials*, in *Orthogonal polynomials: current trends and applications*, vol. 22 of SEMA SIMAI Springer Ser., pp. 309–327, Springer, Cham ([2021] ©2021).
- [78] H. S. WILF, *Generatingfunctionology*, A K Peters, Ltd., Wellesley, MA, third ed. (2006).
- [79] N. S. WITTE, *Semiclassical orthogonal polynomial systems on nonuniform lattices, deformations of the Askey table, and analogues of isomonodromy*, Nagoya Math. J. **219**, 127–234 (2015).
- [80] G. J. YOON, *Darboux transforms and orthogonal polynomials*, Bull. Korean Math. Soc. **39** (3), 359–376 (2002).
- [81] A. ZHEDANOV, *Rational spectral transformations and orthogonal polynomials*, J. Comput. Appl. Math. **85** (1), 67–86 (1997).