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Radium Ion Spectroscopy

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Bibliography

- [1] A. Salam. Gauge unification of fundamental forces. *Rev. Mod. Phys.*, 52(3):525, 1980.
- [2] S. Glashow. Towards a unified theory: Threads in a tapestry. *Rev. Mod. Phys.*, 52(3):539, 1980.
- [3] S. Weinberg. Conceptual foundations of the unified theory of weak and electromagnetic interactions. *Rev. Mod. Phys.*, 52(3):515, 1980.
- [4] M.K. Gaillard, P.D. Grannis, and F.J. Sciulli. The Standard Model of particle physics. *Rev. Mod. Phys.*, 71(2):S96, 1999.
- [5] M.J. Ramsey-Musolf. Nuclear science and the new Standard Model. *Nucl. Phys. A*, 805:138, 2008.
- [6] S. Weinberg. *The quantum theory of fields. Vol. 3: Supersymmetry*. Cambridge University Press, 2000.
- [7] C.T. Hill and E.H. Simmons. Strong dynamics and electroweak symmetry breaking. *Phys. Rept.*, 381:235–402, 2003.
- [8] H. Georgi and S. L. Glashow. Unity of all elementary-particle forces. *Phys. Rev. Lett.*, 32(8):438–441, 1974.
- [9] J. Polchinski. *String Theory*. Cambridge Univ. Press, 1998.
- [10] M. Peskin and T. Takeuchi. Estimation of oblique electroweak corrections. *Phys. Rev. D*, 46(1):381–409, 1992.
- [11] K. Jungmann. Fundamental symmetries and interactions - Some aspects. *Eur. Phys. J. A*, 25:677–683, 2005.
- [12] K. Jungmann. Tests of fundamental symmetries and interactions using nuclei and lasers. *Hyperfine Interact.*, 171:41–55, 2006.

- [13] K. Jungmann. Fundamental symmetries and interactions. *Nucl. Phys. A*, 751:87c–106c, 2005.
- [14] H.W. Wilschut, U. Dammalapati, D.J. van der Hoek, K. Jungmann, W. Kruithof, C.J.G. Onderwater, B. Santra, P.D. Shidling, and L. Willmann. β -decay and the electric dipole moment: Searches for time-reversal violation in radioactive nuclei and atoms. *Pramana J. Phys.*, 75(1):163–170, 2010.
- [15] H.W. Wilschut, D.J. van der Hoek, K. Jungmann, W. Kruithof, C.J.G. Onderwater, B. Santra, P. Shidling, and L. Willmann. β -decay and the electric dipole moment: Searches for time-reversal violation in radioactive nuclei and atoms. *Nucl. Phys. A*, 844:143C–149C, 2010.
- [16] M. Sohani. Setup for precise measurements of β -decay in optically trapped radioactive Na. *Ph.D. Thesis, University of Groningen*, pages 1–180, 2008.
- [17] S. De. Laser cooling and trapping of barium. *Ph.D. Thesis, University of Groningen*, pages 1–148, 2008.
- [18] U. Dammalapati. Metastable D-state spectroscopy and laser cooling of barium. *Ph.D. Thesis, University of Groningen*, pages 1–156, 2006.
- [19] E. Traykov. Production of radioactive beams for atomic trapping. *Ph.D. Thesis, University of Groningen*, pages 1–146, 2006.
- [20] A. Rogachevskiy. Production and trapping of Na isotopes for beta-decay studies. *Ph.D. Thesis, University of Groningen*, pages 1–124, 2007.
- [21] G.P.A Berg, P. Dendooven, O. Dermois, M.N. Harakeh, R. Hoekstra, K. Jungmann, S. Kopecky, R. Morgenstern, A. Rogachevskiy, R. Timmermans, L. Willmann, and H.W. Wilschut. TRI μ P - A radioactive isotope trapping facility under construction at KVI. *Nucl. Instr. Meth. B*, 204:532, 2003.
- [22] C.S. Wood, S.C. Bennett, D. Cho, B.P. Masterson, J.L. Roberts, C.E. Tanner, and C.E. Wieman. Measurement of parity nonconservation and an anapole moment in cesium. *Science*, 275(5307):1759–1763, 1997.
- [23] S.C. Bennett and C.E. Wieman. Measurement of the 6S \rightarrow 7S transition polarizability in atomic cesium and an improved test of the Standard Model. *Phys. Rev. Lett.*, 82(12):2484–2487, 1999.

- [24] S.C. Bennett, J.L. Roberts, and C.E. Wieman. Measurement of the DC stark shift of the $6S \rightarrow 7S$ transition in atomic cesium. *Phys. Rev. A*, 59(1):R16–R18, 1999.
- [25] B.K. Sahoo, L.W. Wansbeek, K. Jungmann, and R.G.E. Timmermans. Light shifts and electric dipole matrix elements in Ba^+ and Ra^+ . *Phys. Rev. A*, 79(5):052512, 2009.
- [26] L.W. Wansbeek, B.K. Sahoo, R.G.E. Timmermans, K. Jungmann, B.P. Das, and D. Mukherjee. Atomic parity nonconservation in Ra^+ . *Phys. Rev. A*, 78(5):050501, 2008.
- [27] J.S.M. Ginges and V.V. Flambaum. Violations of fundamental symmetries in atoms and tests of unification theories of elementary particles. *Phys. Rep.*, 397:63, 2004.
- [28] W.J. Marciano and J.L. Rosner. Atomic parity violation as a probe of new physics. *Phys. Rev. Lett.*, 65(24):2963–2966, 1990.
- [29] S.G. Porsev, K. Beloy, and A. Derevianko. Precision determination of electroweak coupling from atomic parity violation and implications for particle physics. *Phys. Rev. Lett.*, 102(18):181601, 2009.
- [30] M.A. Bouchiat, J. Guena, L. Pottier, and L. Hunter. New observation of a parity violation in Cesium. *Phys. Lett. B*, 134(6):463–468, 1984.
- [31] N. Fortson. Possibility of measuring parity nonconservation with a single trapped atomic ion. *Phys. Rev. Lett.*, 70(16), 1993.
- [32] J.A. Sherman, A. Andalkar, W. Nagourney, and E.N. Fortson. Measurement of light shifts at two off-resonant wavelengths in a single trapped Ba^+ ion and the determination of atomic dipole matrix elements. *Phys. Rev. A*, 78(5):052514, 2008.
- [33] T. Koerber. Measurement of light shift ratios with a single trapped $^{138}Ba^+$ ion, and prospects for a parity violation experiment. *Ph.D. Thesis, University of Washington*, pages 1–240, 2003.
- [34] E.P. Wigner. Events, laws of nature, and invariance principles. *Nobel Lectures Physics, 1963-1970*:6–17, 1963.

- [35] T.D. Newton and E.P. Wigner. Localized states for elementary systems. *Rev. Mod. Phys.*, 21(3):400–406, 1949.
- [36] H.A. Kramers. *Proc. K. Ned. Acad. Wet.*, 40:814, 1937.
- [37] K. Blaum and F. Herfurth. Trapped charged particles and fundamental interactions. *Springer Lecture Notes in Physics 749*, pages 1–192, 2008.
- [38] J. Schwinger. The theory of quantized fields I. *Phys. Rev.*, 82(6):914–927, 1951.
- [39] T. Lee and C. Yang. Question of parity conservation in weak interactions. *Phys. Rev.*, 104(1):254, 1956.
- [40] E.M. Purcell and N.F. Ramsey. On the possibility of electric dipole moments for elementary particles and nuclei. *Phys. Rev.*, 78(6):807, 1950.
- [41] C. Wu, E. Ambler, R. Hayward, and D. Hoppes. Experimental test of parity conservation in beta decay. *Phys. Rev.*, page 1413, 1957.
- [42] Y. Zeldovich. Nonconservation of first order parity in electron scattering and other effects with weak interaction constant. *Zhur. Eksptl'. i Teoret. Fiz.*, 9:682, 1959.
- [43] M.A. Bouchiat and C.C. Bouchiat. Weak neutral currents in atomic physics. *Phys. Lett. B*, 48(2):111–114, 1974.
- [44] T.W. Koerber, M. Schacht, W. Nagourney, and E.N. Fortson. Radio frequency spectroscopy with a trapped Ba⁺ ion: recent progress and prospects for measuring parity violation. *J. Phys. B - At. Mol. Opt.*, 36(3):637–648, 2003.
- [45] J.A. Sherman. Single barium ion spectroscopy: light shifts, hyperfine structure, and progress on an optical frequency standard and atomic parity violation. *Ph.D. Thesis, University of Washington*, pages 1–296, 2009.
- [46] J.A. Sherman, T.W. Koerber, A. Markhotok, W. Nagourney, and E.N. Fortson. Precision measurement of light shifts in a single trapped Ba⁺ ion. *Phys. Rev. Lett.*, 94(24):1–4, 2005.
- [47] D. DeMille, D. Budker, and E.D. Commins. Measurement of the stark-induced amplitudes of the 6P_{1/2}→7P_{1/2} transition in atomic Thallium. *Phys. Rev. A*, 50(6):4657–4670, 1994.

- [48] S. Sanguinetti, J. Guena, M. Lintz, P. Jacquier, A. Wasan, and M.A. Bouchiat. Prospects for forbidden-transition spectroscopy and parity violation measurements using a beam of cold stable or radioactive atoms. *Eur. Phys. J. D*, 25(1):3–13, 2003.
- [49] O.O. Versolato, G.S. Giri, L.W. Wansbeek, J.E. van den Berg, D.J. van der Hoek, K. Jungmann, W.L. Kruithof, C.J.G. Onderwater, B.K. Sahoo, B. Santra, P.D. Shidling, R.G.E. Timmermans, L. Willmann, and H.W. Wilschut. Laser spectroscopy of trapped short-lived Ra^+ ions. *Phys. Rev. A*, 82(1):010501, 2010.
- [50] K. Tsigmatkin, D. Dounas-Frazer, A. Family, J.E. Stalnaker, V.V. Yashchuk, and D. Budker. Observation of a large atomic parity violation effect in ytterbium. *Phys. Rev. Lett.*, 103(7):071601, 2009.
- [51] K. Tsigmatkin, D. Dounas-Frazer, A. Family, J.E. Stalnaker, V.V. Yashchuk, and D. Budker. Parity violation in atomic ytterbium: Experimental sensitivity and systematics. *Phys. Rev. A*, 81(3):032114, 2010.
- [52] J.A. Sherman, T.W. Koerber, A. Markhotok, W. Nagourney, and E.N. Fortson. Precision measurement of light shifts in a single trapped Ba^+ ion. *Phys. Rev. Lett.*, 94(24):243001, 2005.
- [53] D. DeMille. Parity nonconservation in the $6s^2 1S_0 \rightarrow 6s5d^3 D_1$ transition in atomic ytterbium. *Phys. Rev. Lett.*, 74(21):4165–4168, 1995.
- [54] K. Jungmann. Good fortune from a broken mirror. *Physics*, 2:68, 2009.
- [55] F. Hasert, S. Kabe, W. Krenz, and J. Von Krogh. Observation of neutrino-like interactions without muon or electron in the gargamelle neutrino experiment. *Phys. Lett. B*, 46(1):138, 1973.
- [56] C. Prescott, W. Atwood, and R. Cottrell. Parity non-conservation in inelastic electron scattering. *Phys. Lett. B*, 77(3):347, 1978.
- [57] P. Bagnaia, F. Bonaudi, and M. Borghini. Evidence for $Z^0 \rightarrow e^+e^-$ at the CERN $\bar{p}p$ collider. *Phys. Lett.*, 129(1-2):130, 1983.
- [58] G. Arnison, A. Astbury, B. Aubert, C. Bacci, and G. Bauer. Experimental observation of lepton pairs of invariant mass around 95 Gev/c² at the CERN SPS collider. *Phys. Lett. B*, 126(5):398, 1983.

- [59] J. Erler and M.J. Ramsey-Musolf. Weak mixing angle at low energies. *Phys. Rev. D*, 72(7):073003, 2005.
- [60] P. Anthony, R. Arnold, C. Arroyo, and K. Baird. Precision measurement of the weak mixing angle in moeller scattering. *Phys. Rev. Lett.*, 95:018601, 2005.
- [61] G. Zeller, K. McFarland, T. Adams, and A. Alton. Precise determination of electroweak parameters in neutrino-nucleon scattering. *Phys. Rev. Lett.*, 88:091802, 2002.
- [62] The ALEPH, the DELPHI, the L3, the OPAL, the SLD Collaborations, the LEP Electroweak Working Group, The SLD Electroweak, and Heavy Flavour Groups. Precision electroweak measurements on the Z resonance. *Physics Reports*, 427(5-6):257 – 454, 2006.
- [63] A. Akhundov. Precision tests of electroweak interactions. *AIP Conf. Proc.*, 1006:43–48, 2008.
- [64] P. Anthony, R. Arnold, C. Arroyo, and K. Baird. Observation of parity nonconservation in moeller scattering. *Phys. Rev. Lett.*, 92:181602, 2004.
- [65] V. Dzuba and V. Flambaum. Calculations of parity-nonconserving S-D amplitudes in Cs, Fr, Ba⁺, and Ra⁺. *Phys. Rev. A*, 63(6):062101, 2001.
- [66] M.A. Bouchiat and C.C. Bouchiat. Parity violation in atoms. *Rep. Prog. Phys.*, 60:1351–1396, 1997.
- [67] A. Derevianko and S.G. Porsev. Theoretical overview of atomic parity violation. *Eur. Phys. J. A - Hadrons and Nuclei*, 32(4):517–523, 2007.
- [68] E.N. Fortson. Atomic parity nonconservation experiments. *Physics Reports*, 113(5):289–344, 1984.
- [69] M.J.D. Macpherson, K.P. Zetie, R.B. Warrington, D.N. Stacey, and J.P. Hoare. Precise measurement of parity nonconserving optical rotation at 876 nm in atomic bismuth. *Phys. Rev. Lett.*, 67(20):2784–2787, 1991.
- [70] D.M. Meekhof, P. Vetter, P.K. Majumder, S.K. Lamoreaux, and E.N. Fortson. High-precision measurement of parity nonconserving optical rotation in atomic lead. *Phys. Rev. Lett.*, 71(21):3442–3445, 1993.

- [71] P.A. Vetter, D.M. Meekhof, P.K. Majumder, S.K. Lamoreaux, and E.N. Fortson. Precise test of electroweak theory from a new measurement of parity nonconservation in atomic thallium. *Phys. Rev. Lett.*, 74(14):2658–2661, 1995.
- [72] D.M. Lucas, R.B. Warrington, D.N. Stacey, and C.D. Thompson. Search for parity nonconserving optical rotation in atomic samarium. *Phys. Rev. A*, 58(5):3457–3471, 1998.
- [73] C.E. Wieman. Parity nonconservation in atoms - Past work and trapped atom future. *Hyperfine Interact.*, 81(1-4):27–34, 1993.
- [74] S. Sanguinetti, S.N. Atutov, R. Calabrese, L. Corradi, A. Dainelli, A. Khanbekyan, E. Mariotti, C. Mauro, P. Minguzzi, L. Moi, G. Stancari, L. Tomassetti, and S. Veronesi. Prospects for parity violation measurements in cold francium atoms. In *Proceedings of The 3rd Workshop From Parity Violation to Hadronic Structure*, pages 185–187. Springer Berlin Heidelberg, 2007.
- [75] B.K. Sahoo, B.P. Das, R.K. Chaudhuri, D. Mukherjee, R.G.E. Timmermans, and K. Jungmann. Investigations of Ra^+ properties to test possibilities for new optical-frequency standards. *Phys. Rev. A*, 76(4):040504, 2007.
- [76] E. Rasmussen. Serien im Funkenspektrum des Radiums Ra II. *Z. Phys. A - Hadrons and Nuclei*, 86(1-2):24–32, 1933.
- [77] E. Rasmussen. Das bogenspektrum des Radiums. *Z. Phys. A - Hadrons and Nuclei*, 87(9-10):607–615, 1934.
- [78] H. Russell. The spectrum and ionization potential of Radium. *Phys. Rev.*, 46(11):989–990, 1934.
- [79] K. Wendt, S. Ahmad, W. Klempt, and R. Neugart. On the hyperfine structure and isotope shift of radium. *Z. Phys. D*, 4:227–241, 1987.
- [80] S. Ahmad, W. Klempt, R. Neugart, and E. Otten. Determination of nuclear spins and moments in a series of radium isotopes. *Phys. Lett. B*, 133(1-2):47–52, 1983.

- [81] W. Neu, R. Neugart, E. Otten, G. Passler, and K. Wendt. Quadrupole moments of radium isotopes from the $7^2P_{3/2}$ hyperfine structure in Ra II. *Z. Phys. D.*, 11:105–111, 1989.
- [82] S.A. Ahmad, W. Klempt, R. Neugart, E.W. Otten, P.G. Reinhard, G. Ulm, and K. Wendt. Mean-square charge radii of radium isotopes and octupole deformation in the $^{220-228}\text{Ra}$ region. *Nucl. Phys. A*, 483(2):244–268, 1988.
- [83] E. Arnold, W. Borchers, M. Carre, H.T. Duong, P. Juncar, J. Lerme, S. Liberman, W. Neu, R. Neugart, E.W. Otten, M. Pellarin, J. Pinard, G. Ulm, J.L. Vialle, and K. Wendt. Direct measurement of nuclear magnetic moments of radium isotopes. *Phys. Rev. Lett.*, 59(7):771–774, 1987.
- [84] R. Pal, D. Jiang, and M. Safronova. Calculation of parity-nonconserving amplitude and other properties of Ra^+ . *Phys. Rev. A*, 79(6):062505, 2009.
- [85] B.K. Sahoo, R.G.E. Timmermans, B.P. Das, and D. Mukherjee. Comparative studies of dipole polarizabilities in Sr^+ , Ba^+ , and Ra^+ and their applications to optical clocks. *Phys. Rev. A*, 80:062506, 2009.
- [86] J. Emsley. *The elements*. Oxford Univ. Press, 1995.
- [87] B.K. Sahoo, Md. R. Islam, and D. Mukherjee. Lifetimes of the metastable $^2D_{3/2,5/2}$ states in Ca^+ , Sr^+ , and Ba^+ . *Phys. Rev. A*, 74(6):1–6, 2006.
- [88] V.A. Dzuba and V.V. Flambaum. Calculation of nuclear-spin-dependent parity nonconservation in S-D transitions of Ba^+ , Yb^+ and Ra^+ ions. *arXiv:1104.0086v1 [physics.atom-ph]*, 2011.
- [89] L.W. Wansbeek. *Ph.D. Thesis, University of Groningen*, 2011.
- [90] Web page of Accelerator and Ion Source Research at KVI, <http://www.rug.nl/kvi/Research/acceleratorPhysics/index>.
- [91] P.D. Shidling, G.S. Giri, D.J. van der Hoek, K. Jungmann, W. Kruithof, C.J.G. Onderwater, M. Sohani, O.O. Versolato, L. Willmann, and H.W. Wilschut. Production of short lived radioactive beams of radium. *Nucl. Instr. Meth. A*, 606(3):305–309, 2009.
- [92] A. Gavron. Statistical model calculations in heavy ion reactions. *Phys. Rev. C*, 21(1):230–236, 1980.

- [93] G.P.A. Berg, O.C. Dermois, U. Dammalapati, P. Dendooven, M.N. Harakeh, K. Jungmann, C.J.G. Onderwater, A. Rogachevskiy, M. Sohani, E. Traykov, L. Willmann, and H.W. Wischut. Dual magnetic separator for TRI μ P. *Nucl. Instr. Meth. A*, 560(2):169–181, 2006.
- [94] E. Traykov, A. Rogachevskiy, M. Bosswell, U. Dammalapati, P. Dendooven, O.C. Dermois, K. Jungmann, C.J.G. Onderwater, M. Sohani, L. Willmann, H.W. Wilschut, and A.R. Young. Production of radioactive nuclides in inverse reaction kinematics. *Nucl. Instr. Meth. A*, 572(2):580–584, 2007.
- [95] O.B. Tarasov and D. Bazin. Lise++: Radioactive beam production with in-flight separators. *Nucl. Instr. and Meth. B*, 266(19-20):4657 – 4664, 2008.
- [96] E. Traykov, U. Dammalapati, S. De, O.C. Dermois, L. Huisman, K. Jungmann, W. Kruithof, A.J. Mol, C.J.G. Onderwater, A. Rogachevskiy, M. da Silva e Silva, M. Sohani, O. Versolato, L. Willmann, and H.W. Wilschut. Development of a thermal ionizer as ion catcher. *Nucl. Instr. Meth. B*, 266(19-20):4478–4482, 2008.
- [97] G. Savard et al. Development and operation of gas catchers to thermalize fusion-evaporation and fragmentation products. *Nucl. Instr. Meths. B*, 204:582 – 586, 2003.
- [98] P. Dendooven, S. Purushothaman, and K. Gloos. On a cryogenic noble gas ion catcher. *Nucl. Instr. Meths. A*, 558(2):580 – 583, 2006.
- [99] G. Bollen, D.J. Morrissey, and S. Schwarz. A study of gas-stopping of intense energetic rare isotope beams. *Nucl. Instr. Meths. A*, 550(1-2):27 – 38, 2005.
- [100] Decay Data Home Page, Isotopes Project, Nuclear Science Division, LBNL, <http://ie.lbl.gov/decay.html>.
- [101] P.D. Shidling, G.S. Giri, D.J. van der Hoek, K. Jungmann, W.L. Kruithof, C.J.G. Onderwater, B. Santra, M. Sohani, O.O. Versolato, L. Willmann, and H.W. Wilschut. Thermalization of different alkali and alkali-earth elements at the TRI μ P facility. *Nucl. Instr. Meth. A*, 622(1):11–16, 2010.
- [102] W. Paul, H. Reinhard, and U. von Zahn. Das Elektrische Massenfilter als Massenspektrometer und Isotopentrenner. *Z. Phys. A - Hadrons and Nuclei*, 152(2):143–182, 1958.

- [103] M. Knoop, M. Vedel, and F. Vedel. Collisional quenching and j-mixing rate constants for the 3D levels of Ca^+ . *Phys. Rev. A*, 58(1):264–269, 1998.
- [104] C.E. Wieman. Frequency stabilization of a diode laser using simultaneous optical feedback from a diffraction grating and a narrowband fabry–perot cavity. *Rev. Sci. Instrum.*, 1991.
- [105] H. Patrick and C. Wieman. Using diode lasers for atomic physics. *Rev. Sci. Instrum.*, 62(11):25933–2595, 1991.
- [106] P.A. Franken, A.E. Hill, C.W. Peters, and G. Weinreich. Generation of optical harmonics. *Phys. Rev. Lett.*, 7(4):118–119, 1961.
- [107] C.J. Foot. *Atomic physics*. Oxford Univ. Press, 2005.
- [108] S. Gerstenkorn, J. Verges, and J. Chevillard. *Atlas du spectre d’Absorption de la Molecule de d’iode*, CNRSII, Laboratoire Aim Cotton, 91405 Orsay (France)(11.000 cm^{-1} -14.000 cm^{-1} edition), 1982.
- [109] U. Dammalapati, S. De, K. Jungmann, and L. Willmann. Isotope shifts of $6s5d^3\text{D}$ - $6s6p^1\text{P}_1$ transitions in neutral barium. *Eur. Phys. J. D*, 53(1):1–8, 2009.
- [110] J. Cariou and P. Luc. *Atlas du spectre d’Absorption de la Molecule de Tellure*, CNRS, Paris, 1980.
- [111] Web page of CERN ROOT, <http://root.cern.ch/>.
- [112] G.K. Woodgate. *Elementary Atomic Structure*. Oxford University Press, 1983.
- [113] B.H. Bransden and C.J. Joachain. *The Physics of Atoms and Molecules*. Pearson Education Limited, 2003.
- [114] A.-M. Mårtensson–Pendrill and A. Ynnerman. Isotope shift and nuclear charge radii of barium isotopes. *J. Phys. B*, 25:551, 1992.
- [115] W.H. King. Peculiarities of the isotope shift in the samarium spectrum. *J. Opt. Soc. Am.*, 53(5):638, 1963.
- [116] Atomic Weights and Isotopic Compositions, NIST Standard Reference Database 144, <http://www.nist.gov/pml/data/comp.cfm>.

- [117] N. Yu, W. Nagourney, and H. Dehmelt. Radiative lifetime measurement of the Ba^+ metastable $D_{3/2}$ state. *Phys. Rev. Lett.*, 78(26):4898–4901, 1997.
- [118] H.J. Metcalf and P. van der Straten. *Laser cooling and trapping*. Springer, 1999.
- [119] H. Dehmelt. Radiofrequency spectroscopy of stored ions II: Spectroscopy. *Advances in Atomic and Molecular Physics*, 1969.
- [120] O.O. Versolato. *Ph.D. Thesis, University of Groningen*, 2011.
- [121] F. Major, V. Gheorghe, and G. Werth. *Charged Particle Traps: Physics and Techniques of Charged Particle Field Confinement*. Springer Series on Atomic, Optical, and Plasma Physics, 2005.
- [122] P.K. Ghosh. *Ion Traps*. Oxford Univ. Press, 1995.
- [123] W. Paul. Electromagnetic traps for charged and neutral particles. *Rev. Mod. Phys.*, 62(3):531–542, 1990.
- [124] F. Penning. Die Glimmentladung bei niedrigem Druck zwischen koaxialen Zylindern in einem axialen Magnetfeld. *Physica Scripta*, 3(9):873–894, 1936.
- [125] H. Dehmelt. Radiofrequency spectroscopy of stored ions I: Storage. *Advances in Atomic and Molecular Physics*, 1968.

