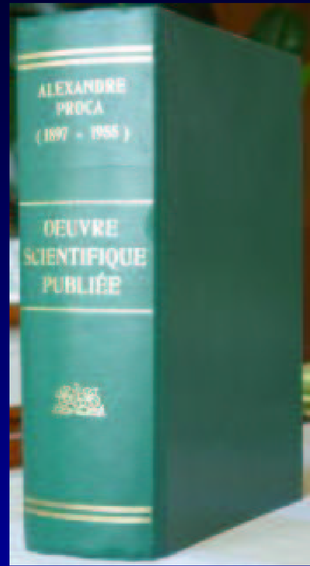
ALEXANDRU PROCA

(1897–1955)



Dorin POENARU

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Frankfurt am Main, Germany

OUTLINE

- Chronology
- Impact on various branches of theoretical physics
- Particles
- Relativistic quantum fields
- Klein-Gordon fields
- Dirac field
- Maxwell and Proca field
- Hideki Yukawa and the Strong interaction
- Einstein-Proca gravity. Dark matter, black holes. Tachyons.

Chronology I

- 1897 October 16: born in Bucharest
- 1915 Graduate of the *Gheorghe Lazar* high school
- 1917–18 Military School and 1st world war
- 1918–22 student Polytechnical School (PS), Electromechanics
- 1922–23 Engineer Electrical Society, Câmpina, and assistant professor of Electricity, PS Bucharest
- 1923 Move to France: *"I have something to say in Physics"*
- 1925 Graduate of Science Faculty, Sorbonne University, Paris

Chronology II

- 1925–27 researcher, Institut du Radium. Appreciated by Marie Curie
- 1930–31 French citizen. L. de Broglie's PhD student. Marie Berthe Manolesco became his wife
- 1931–33 Boursier de Recherches, Institut Henri Poincaré
- 1933 PhD thesis. Commission: Jean Perrin, L. Brillouin, L. de Broglie. Chargé de Recherches. After many years Proca will be Directeur de Recherches
- 1934 One year with E. Schrödinger in Berlin and few months with N. Bohr in Copenhagen (met Heisenberg and Gamow)

Chronology III

- 1936–41 Proca equations. Massive spin-1 quantum field
- 1938 Papers related to Proca eqs. by Yukawa, Wentzel, Taketani, Sakata, Kemmer, Heitler, Fröhlich, Bhabha
- 1939 Proca invited to attend the Solvay Congress. 2nd world war. Chief Engineer of the French Radiobroadcasting Company
- 1949 H Yukawa — Nobel prize for the meson theory of nuclear forces
- 1943 Lectures at University of Portô, Portugal
- 1943–45 UK: invited by Royal Society and British Admiralty to join the war effort.

Chronology IV

- 1946 start the *Proca Seminar* with many prestigious invited speakers
- 1949 and 1950 Attempts to get a chair of Physics at the Sorbonne University and College de France failed
- 1950 with P. Auger organizers of the Theoretical Physics Colloquium of CNRS
- 1951 French delegate, General Meeting of International Union of Physics
- 1953–55 laryngeal cancer
- 1955 December 13: A. Proca passed away

PACS *(Physics & Astronomy Classification Scheme)*

- *03. Quantum mechanics, field theories, and special relativity*
  - 03.50.-z Classical field theories
  - 03.50.De Classical electromagnetism, Maxwell equations
  - 03.70.+k Theory of quantized fields
- *04. General relativity and gravitation*
  - 04.50.+h Gravity in more than four dimensions, Kaluza-Klein theory, unified field theories; alternative theories of gravity
  - 04.60.-m Quantum gravity
  - 04.70.-s Physics of black holes
  - 04.70.Bw Classical black holes
  - Quantum aspects of black holes, evaporation, thermodynamics
- *11. General theory of fields and particles*
  - 11.10.-z Field theory
  - 11.10.Kk Field theories in dimensions other than four
  - 11.15.-q Gauge field theories
  - 11.30.Cp Lorentz and Poincare invariance
- *12. Specific theories and interaction models; particle systematics*
  - 12.20.-m Quantum electrodynamics
  - 12.38.-t Quantum chromodynamics
  - 12.40.Vv Vector-meson dominance

Particles

The projection of angular momentum is $l_z\hbar$, with l_z integer $-l \leq l_z \leq l$. The intrinsic angular momentum, s, is called spin.

- fermions, $s = (n + 1/2)\hbar$, n integer
  - spinor, $s = \hbar/2$, e.g. leptons (e, ν, μ, τ)
  - spinor-vector, $s = (3/2)\hbar$
- bosons, $s = n\hbar$
  - scalar, $s = 0$,
  - vector, $s = \hbar$, e.g. mesons (ω, ρ), $m = 0$ photons,
    weak (massive $W^{\pm}, Z^0$ bosons), $m = 0$ gluons
  - tensor, $s = 2\hbar$, e.g. graviton

Vector bosons are mediators of three (of the four) fundamental interactions in particle physics: electromagnetic, weak, and strong. Tensor bosons are assumed to mediate the gravitation.

Fundamental interactions

FORCE	RANGE	TRANSMITTED BY BOSONS
gravity	long	graviton, massless, spin 2
electro-magnetism	long	photon (γ), massless, spin 1
weak interaction	short	$W^{\pm}$, Z^{0}, heavy, spin 1
strong interaction	short	gluons (g), massless, spin 1

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Relativistic quantum fields

A particle is a localized entity. A field occupies a region of space. Einstein's special theory of relativity allows for the existence of scalar, vector, tensor, fields. Examples

- Klein-Gordon ($s = 0$)
- Dirac ($s = 1/2$)
- Proca ($s = 1$, $m \neq 0$)
- Maxwell ($s = 1$, $m = 0$)
- Rarita-Schwinger ($s = 3/2$)
- Gravitation ($s = 2$)

Relativistic notations I

Natural units: $\hbar = c = 1$**.** $G = M_{Pl}^{-2}$. $M_{Pl} = 1.22 \times 10^{19}$ GeV

Four vector $a^\mu = (a^0; a^1, a^2, a^3)$, $a_\mu = (a_0; a_1, a_2, a_3)$,

$x^\mu = (t; x, y, z) = (x^0; x^1; x^2; x^3)$, $p^\mu = (E; \vec{p}\,)$

A metric tensor (covariant components)

$$g_{\mu\nu} = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix}$$

$a_\mu = g_{\mu\nu} a^\nu$. Einstein's convention: summ over repetead indices.

Scalar prod. $a_\mu b^\mu = a^0 b^0 - a^1 b^1 - a^2 b^2 - a^3 b^3 = a^0 b^0 - \vec{a}\vec{b}$

Contravariant form $g^{\mu\nu} = g_{\mu\nu}$.

Relativistic notations II

Derivatives

$$\partial^\mu = \frac{\partial}{\partial x^\mu} = \left(\frac{\partial}{\partial t}; -\frac{\partial}{\partial x}, -\frac{\partial}{\partial y}, -\frac{\partial}{\partial z}\right) = (\partial^0; -\nabla); \;\; \partial_\mu = \frac{\partial}{\partial x^\mu} = (\partial^0;\; \nabla)$$

$$\partial_\mu a^\mu = \frac{\partial a^0}{\partial t} + \nabla\vec{a}$$

$$\partial_\mu \partial^\mu = \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} = \partial_0^2 - \nabla^2 = \partial^\mu \partial_\mu = \Box$$

∇^2 - the Laplacian. $\Box = \left(\frac{\partial^2}{\partial t^2} - \nabla^2\right)$ - the d'Alembertian

Volume elements

$d^4x = d^3x dt = d^3x dx^0 \;;\;\; d^3x = dxdydz = dx^1 dx^2 dx^3$

Lagrangian

$L = T - V$, T - kinetic energy, V - potential. The classical action $S = \int_{t_1}^{t_2} L dt$ is minimized to get the eqs. of motion (Newton's 2nd law in classical mechanics).

In field theory (the field $\varphi(x)$) the Lagrangian density is a functional integrated over all space-time

$$\mathcal{S}[\varphi_i] = \int \mathcal{L}[\varphi_i, \partial_\mu \varphi] \, d^4x$$

The Lagrangian is the spatial integral of the density.

The least action principle leads to Euler-Lagrange equations

$$\frac{\delta}{\delta\varphi}\mathcal{S} = -\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \varphi)} \right) + \frac{\partial \mathcal{L}}{\partial \varphi} = 0$$

Natural units: $\hbar = c = 1$

Klein-Gordon field

For a massive ($m \neq 0$) scalar (spin 0) and neutral (charge zero) field, the Lagrangian density (function of the fields ϕ and their x, y, z, t derivatives) is

$$\mathcal{L} = (1/2)[(\partial_\mu \phi)(\partial^\mu \phi) - m^2 \phi^2]$$

The Euler-Lagrange formula requires

$$(\Box + m^2)\phi = 0$$

i.e. the Klein-Gordon eq. It was quantized by Pauli and Weisskopf. Relativistic wave equations are invariant under Lorentz transformations, expressing the invariance of the element of 4-vector length $ds^2 = dt^2 - (dx^2 + dy^2 + dz^2)$.

Dirac field I

For a massive spinor (spin $1/2$) field the Lagrangian density is

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi \ \ ; \quad \bar{\psi} = \psi^* \gamma^0 \ \ Dirac \ \ adjoint$$

where the four 4×4 Dirac matrices γ^μ ($\mu = 0, 1, 2, 3$) satisfy the Clifford algebra $\{\gamma^\mu, \gamma^\nu\} = \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2g^{\mu\nu}$
The corresponding equation of motion is the Dirac eq

$$(i\gamma^\mu \partial_\mu - m)\psi = 0 \ \ ; \quad i(\partial_\mu \bar{\psi})\gamma^\mu + m\bar{\psi} = 0$$

The energy spectrum: positive eigenvalues and negative eigenvalues, which are problematic in view of Einstein's energy of a particle at rest $E = mc^2$. Antiparticles.

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Dirac field II

One set of matrices is

$$\gamma^0 = \begin{pmatrix} I & 0 \\ 0 & I \end{pmatrix}, \quad \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}$$

with identity and zero 2×2 matrices, and Pauli matrices:

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \ \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \ \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Quantization of the Dirac field is achieved by replacing the spinors by field operators and using the Jordan and Wigner quantization rules. Heisenberg's eq. of motion for the field operator $\hat{\psi}(\vec{x}, t)$ reads $i\frac{\partial}{\partial t}\hat{\psi}(\vec{x}, t) = [\hat{\psi}(\vec{x}, t), \hat{H}]$

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Maxwell field I

In classical field theory the differential form of Maxwell eqs. are given by Gauss's, Ampère's and Faraday's laws + Maxwell's extensions. For homogeneous materials:

$$\nabla \cdot \vec{D} = \rho \; ; \quad \nabla \cdot \vec{B} = 0 \; ; \quad \vec{D} = \varepsilon \vec{E} \; ; \quad \vec{B} = \mu \vec{H}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B}/\mu = \vec{j} + \varepsilon \frac{\partial \vec{E}}{\partial t}$$

Photons assumed to be massless. Electrodynamics is gauge invariant (φ and $\vec{A}$ are not unique): Maxwell eqs. do not change under gauge transf. (with χ a differentiable arbitr. function)

$$\vec{A} \rightarrow \vec{A} + \nabla \chi(\vec{r}) \; ; \quad \varphi \rightarrow \varphi - \frac{\partial \chi}{\partial t}$$

Maxwell field II

The 4-potential and current density are

$A^\mu = (\varphi; \vec{A}\,) = (A^0; \vec{A}\,)$, $\; j^\mu = (\rho; \vec{j}\,)$. Scalar and vector potential

$\vec{E} = -\nabla\varphi - \partial\vec{A}/\partial t$, $\; \vec{B} = \nabla \times \vec{A}$. The four vector potential

$A^\mu = (\varphi, \vec{A})$. $\; g_{\mu\nu}A^\mu A^\nu = \varphi^2 - A^2$.

The antisymmetric field-strength tensor $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ with components $F^{0i} = \partial^0 A^i - \partial^i A^0 = -E^i$ and

$F^{ij} = \partial^i A^j - \partial^j A^i = -\epsilon^{ijk}B^k$. The Levi-Civita symbol ϵ^{ijk} is antisymmetric under exchange of any two indices.

The Lagrangian density is

$\mathcal{L} = (E^2 - B^2)/2 - \rho V + \vec{j}\vec{A} = -(1/4)F_{\mu\nu}F^{\mu\nu} - j_\mu A^\mu$

The corresponding Euler-Lagrange eqs. are Maxwell's eqs.

Kaluza and Klein attempted to unify the gravitation and elmg. theories by extending general relativity in 5 dimensions.

Proca field I

Proca extended the Maxwell eqs. in quantum field theory. For massive positively charged particles with spin in 1934 there were two alternatives: Dirac $(\pm E, +q, s \neq 0)$ or Pauli-Weisskopf based on Gordon eqs. $(\pm E, \pm q, s = 0)$. Proca introduced $\pm E, \pm q, s \neq 0$.

For a massive vector boson (spin 1) field the Proca equation

$$\boxed{\Box A^\nu - \partial^\nu(\partial_\mu A^\mu) + m^2 A^\nu = j^\nu}$$

is obtained as a Euler-Lagrange eq. emerging from the Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu - j_\mu A^\mu$$

Proca field II

after expressing the field-strength tensor $F^{\mu\nu}$ in terms of the four potential A^μ. The Maxwell field is a massless ($m = 0$) Proca field. In contrast to the Maxwell field the Lorentz condition is fulfilled by Proca field.

Assuming $m \neq 0$ one has $\partial_\nu A^\mu = (1/m^2)\partial_\nu j^\nu$.

If the source current is conserved ($\partial_\nu j^\nu = 0$) or if there are no surces ($j^\nu = 0$) it follows $\partial_\nu A^\nu = 0$. The field eq. gets simplified $(\Box + m^2)A^\nu = 0$ for free particles.

Louis de Broglie (Nobel Prize in 1929 for discovery of wave nature of particles) did not nominated A. Proca to share the Nobel prize with Yukawa.

Hideki Yukawa (1907-1981)

Nobel Prize in 1949 *for his prediction (in 1934) of the existence of mesons on the basis of theoretical work on nuclear forces*. His potential (of a Debye type) $g^2e^{-\lambda r}/r$ can explain the short range of the strong interaction. There was no link between the quantum theory of fields and nuclear theory, except the Fermi's β-decay theory. Yukawa calculated a mass $\sim 200m_e$ (m_e is the electron mass). By analogy with photons mediating the elmg. interaction he assumed the nuclear forces, acting between nucleons, are mediated by such bosons. They should appear in the high energy cosmic radiation. Yukawa employed a scalar field equation. The right vector field was introduced by Proca. Cecil Powell (Nobel prize in 1950) discovered in 1947 the π-mesons (pions) in cosmic rays.

Quotations from Wolfgang Pauli

Relativistic field theories of elementary particles, *Rev. Mod. Phys.*, **13** (1941) 213: "**2. Wave fields for particles of spin 1***(a) The c number theory for case of no external fields.*—This case holds the center of current interest since Yukawa supposed the meson to have the spin 1 in order to explain the spin dependence of the force between proton and neutron. The theory for this case has been given by Proca."

Exclusion principle and quantum mechanics, *Nobel lecture, December 13,1946*, http://nobelprize.org/physics/laureates/1945/index.html: "The simplest cases of one-valued fields are the scalar field and a field consisting of a four-vector and an antysimmetric tensor like the potentials and field strengths in Maxwell's theory. While the scalar field is simply fulfilling the usual wave equation of the second order in which the term proportional to μ^2 has to be included, the other field has to fulfill equations due to Proca which are generalization of Maxwell's equations which become in the particular case $\mu = 0$."

Strong interaction (color force)

The name meson means middle-weight between electron and nucleon. Cosmic rays contained two intermediate mass particles: muon and pion. The muon is a lepton (a heavy counterpart to the electron) but the pion was a true meson of the kind predicted by Yukawa.

Presently according to quantum chromodynamics, the strong interaction, mediated by massless gluons, affects only quarks and antiquarks; it binds quarks to form hadrons (including p and n). There are 8 types of gluons.

The theory of massive vector bosons with spin 1 was developed by A. Proca. Vector bosons ($W^{\pm}$ and Z^{0} bosons) are mediators of the weak interaction Proca's equations are also used to describe spin 1 mesons, e.g. ρ and ω mesons.

1948

PHYSICAL REVIEW VOLUME 76, NUMBER 1 JULY 1, 1949

The Interaction Representation of the Proca Field

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(Received December 16, 1948)

The methods used by Schwinger in quantum electrodynamics can be generalized in such a way that they become applicable to meson theory. This is shown by an example. The method used seems slightly simpler than the method proposed by the Japanese school. It turns out that the covariant field variables in interaction representation are not simply the transformed of the covariant variables used in Heisenberg representation. Also it turns out to be necessary to confine the space-like surfaces used in many applications to flat surfaces perpendicular to the time direction. The direct interaction between two particles through the meson field is obtained by a canonical transformation similar to the first approximation Schwinger transformation in quantum electrodynamics.

The example of a neutral vector meson field discussed in the present paper has been chosen in such a way as to show the analogy to quantum electrodynamics. The interaction energy between particles obtained by Schwinger's relativistic treatment in meson theory (and also obtainable by the other usual perturbation methods) goes over into the Møller interaction for vanishing meson mass.

INTRODUCTION

IN recent developments of quantum electrodynamics much use has been made of the so-called interaction representation, in which the q-numbers describing various fields of particles or quanta satisfy field equations of a form as if no interactions between these fields would exist, while the interaction is described by a generalized Schroedinger equation for the situation functional (Schroedinger state vector) Ψ. The theory of this interaction representation had been developed independently and published earlier by Tomonaga[2] in Japan. As the theory may be considered as a generalization of the many-times theory of Dirac, Fock, and Podolsky,[3] the new theory was called by him the "super-many-time theory."[4]

If one tries to apply the super-many-time forma-

[2] S. Tomonaga, Bull. I.P.C.R. (Riken-iho) 22, 545 (1943) (*in Japanese*); Prog. Theor. Phys. 1, 27 (1946) and 2, 101 (1947).

1975

Commun. math. Phys. 41, 267—271 (1975)

The Connection between an Euclidean Gauss Markov Vector Field and the Real Proca Wightman Field

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Mathematics Department, Bedford College, London, England

Received August 12, 1974; in revised form October 16, 1974

Abstract. We construct an Euclidean Gauss Markov Vector Field which leads to the Real Proca Wightman Field describing particles of mass >0 and spin 1, for space-time dimension equal to 4.

1999

Class. Quantum Grav. **16** (1999) 2471–2478. Printed in the UK PII: S0264-9381(99)99847-7

Isomorphism between non-Riemannian gravity and Einstein–Proca–Weyl theories extended to a class of scalar gravity theories

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Abstract. We extend the recently proved relation between certain models of non-Riemannian gravitation and Einstein–Proca–Weyl theories to a class of scalar gravity theories, this is used to present a black-hole dilaton solution with non-Riemannian connection.

PACS numbers: 0430J, 0450, 0425D, 0440N, 0470

2004

International Journal of Theoretical Physics, Vol. 43, No. 6, June 2004 (© 2004)

Proca Effect in Kerr–Newman Metric

Xiaomin Bei,[1,2] Changsheng Shi,[1] and Zhongzhu Liu[1]

Received

The Proca effect of an electric field is studied in curved space. A Kerr–Newman metric with the photon rest mass can be presented by the analytic continuation (Xu, C. M. (. . . .). *General Relativity* and *Modern Cosmology*, Nanking Normal University) in a short range. It yields the correction in the Kerr–Newman space.

KEY WORDS: Kerr–Newman spacetime; Proca equation; analytic continuation.

1. INTRODUCTION

The Proca equation for photon is the natural extension of the Maxwell equation in the electrodynamics to case with the rest mass (Goldhaber and Nieto, 1971; Proca, 1936). The equation was studied also in curved space that an exact solution for an idealized point particle has yet to be found (Kramer *et al.*, 1980; Tucker, private Communication). The Einstein–Proca system has been discussed frequently in the articles, for example in Dereli *et al.* (1996), and has been invoked by Tucker

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Nonzero photon mass

Massive electromagnetic field described by Maxwell-Proca eqs.

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} - \mu_\gamma^2 \varphi \; ; \quad \nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \; ; \quad \nabla \times \vec{B} = \mu_0 \vec{j} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} - \mu_\gamma^2 \vec{A}$$

where $\mu_\gamma^{-1} = \hbar/(m_\gamma c)$ Compton wave-length of a photon with mass m_γ. Implications of a massive photon: variation of c, longitudinal elmg. radiation and gravitational deflection, possibility of charged black holes, the existence of magnetic monopoles [14], modification of the standard model [15], etc. An upper limit for the photon rest mass [16] is

$$m_\gamma \leq 1 \times 10^{-49} \text{ g} \equiv 6 \times 10^{-17} \text{ eV.}$$

Superluminal radiation field

Superluminal (faster than light) particles, *tachyons*, with an imaginary mass of the order of $m_e/238$, can be described by a real Proca field with a negative mass square [19-21]. They could be generated in storage rings, jovian magnetosphere, and supernova remnants.

Other developments: Proca-Wightman field [22]; Maxwell-Chern-Simons-Proca model [23]; gauge theory of gravity [24].

Einstein-Proca field eqs. are frequently discussed in connections with dark matter gravitational interactions [17]. At the level of string theories there are hints that non-Riemannian models, such as Einstein-Proca-Weyl theories [18] may be used to account for the dark matter.

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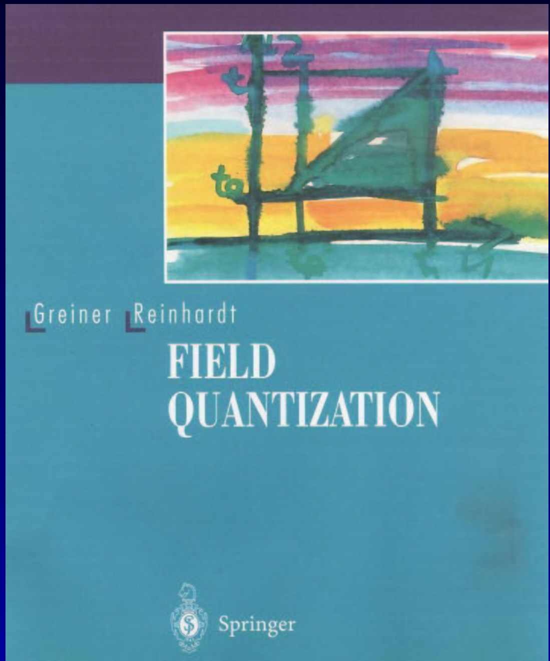
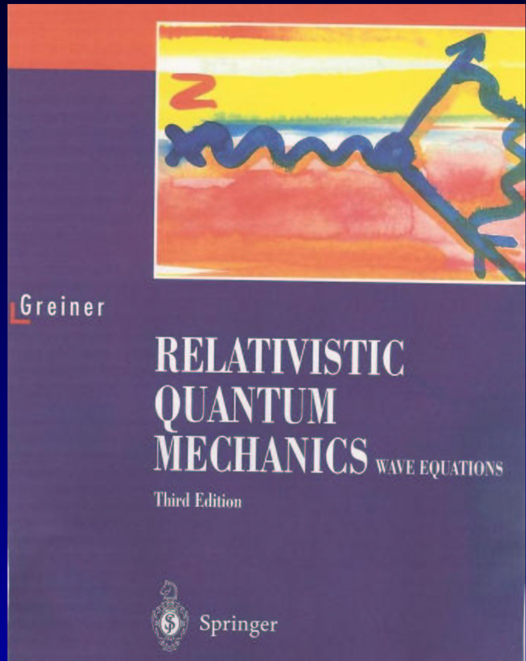
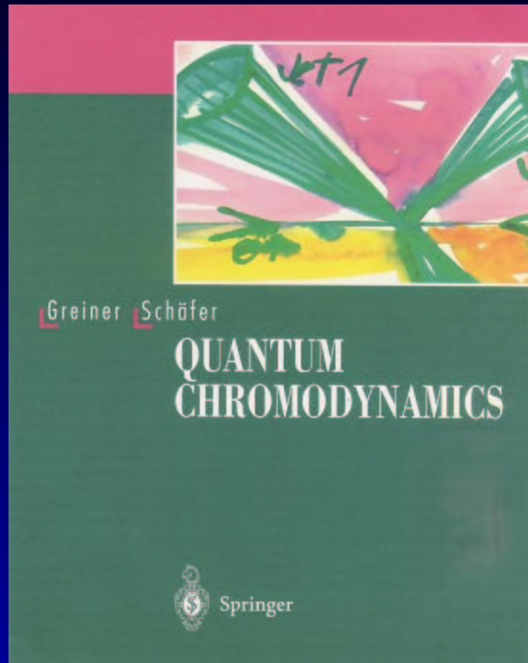
Further reading



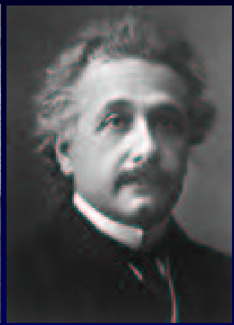




Photographies

James Clerk Maxwell

(1831-1879)

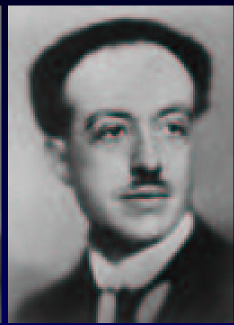


Albert Einstein

(1879-1955) N 1921

Erwin Schrödinger

(1887-1961) N 1933



Louis-Victor Pierre Raymond de Broglie
(1892-1987) N 1929

Alexandru Proca

(1897-1955)

Wolfgang Pauli

(1900-1958) N 1945

Enrico Fermi

(1901-1954) N 1938

Werner Karl Heisenberg
(1901-1976) N 1932

Paul Adrien Maurice Dirac
(1902-1984) N 1933

Cecil Frank Powell

(1903-1969) N 1950

Sin-Itiro Tomonaga

(1906-1979) N 1965

Hideki Yukawa

(1907-1981) N 1949

Three Japanese Nobel prize winners (Yukawa, Tomonaga and Leo Esaki) graduated the same highschool in Kyoto.