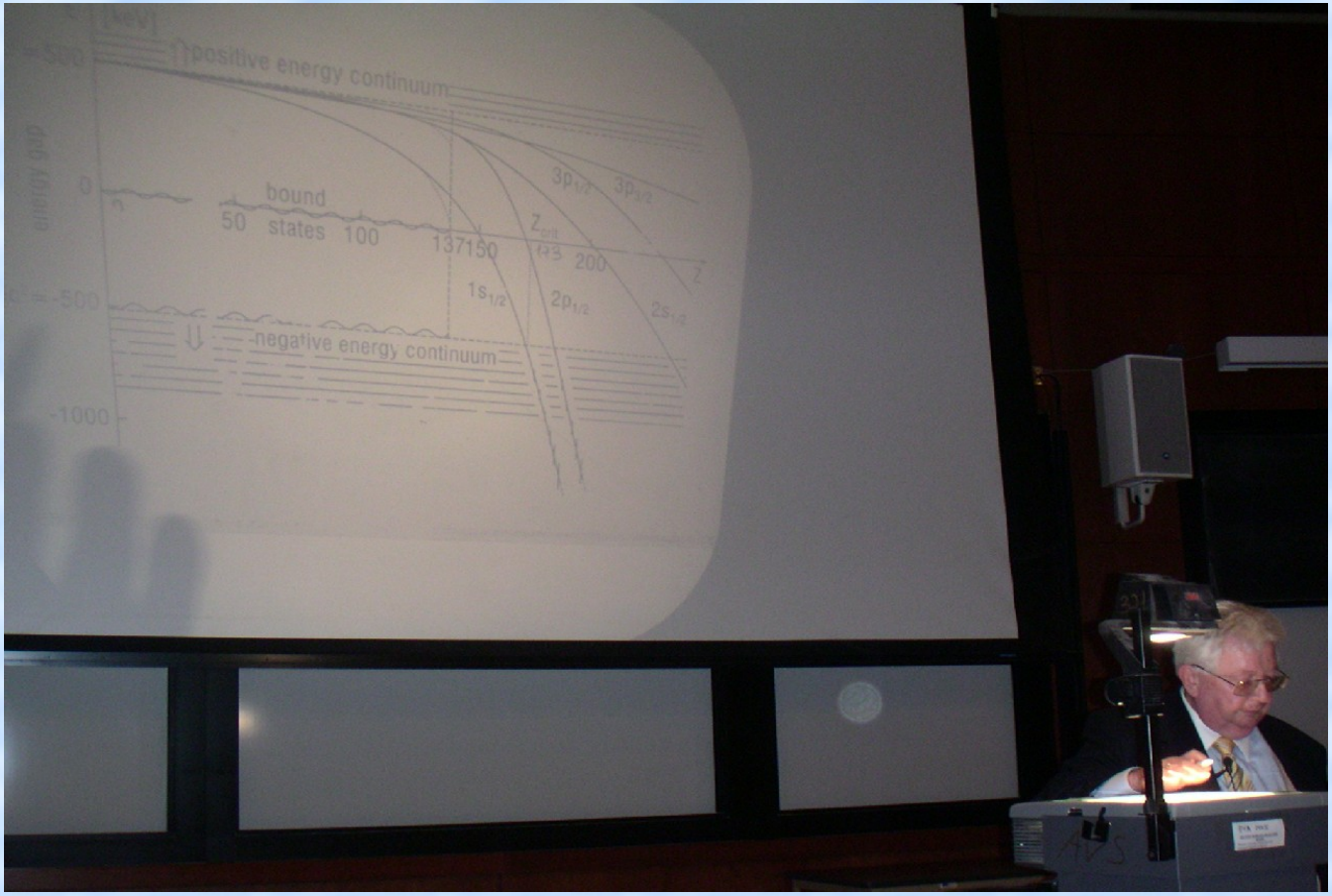
Physics of Strong Fields
A: Reminiscences

By Johann Rafelski – Arizona

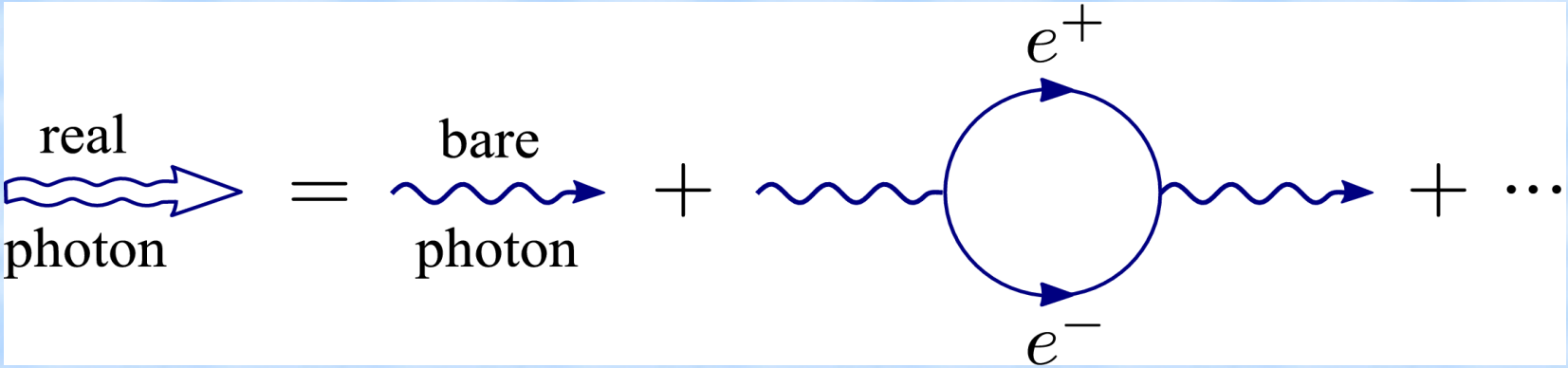
A new field of physics was created in Frankfurt beginning in 1968 – coincident with my meeting in classroom of my future thesis adviser and teacher Walter Greiner. The trigger of his interest was possible creation of superheavy elements

Physics of Strong Fields
B: Foundations and Applications
Thursday 26 Nov 2015

What this is all about:
<u>a passion for strong fields</u>



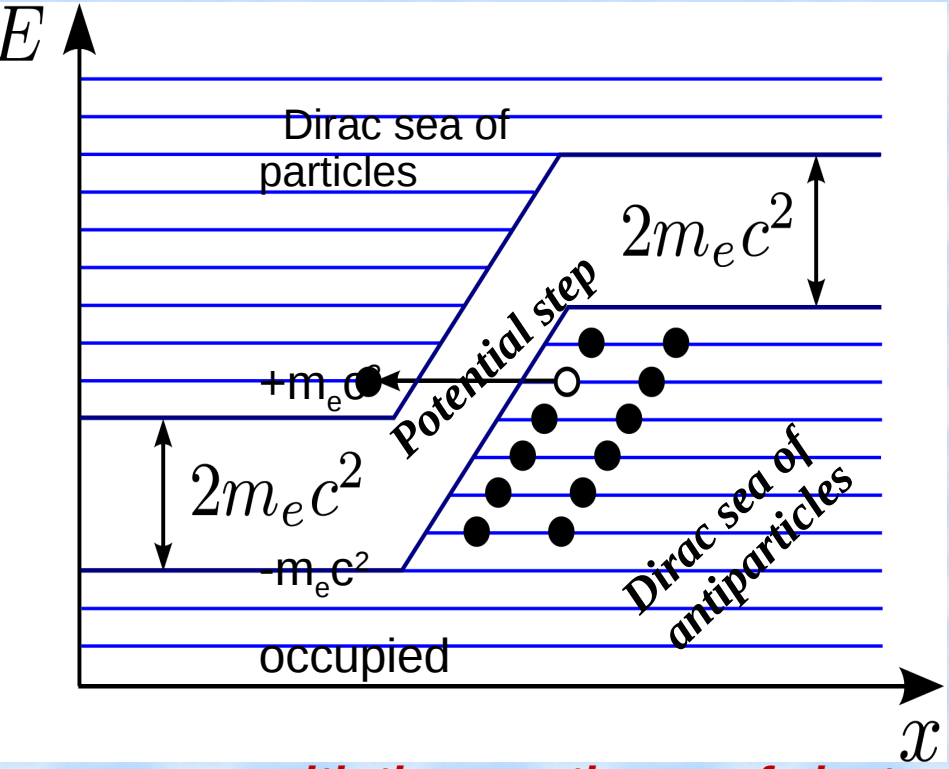
Before WG ERA: Virtual Pairs: The vacuum is dielectric



The vacuum is a dielectric medium: a charge is screened by particle-hole (pair) excitations. In Feynman language the real photon is decomposed into a bare photon and a photon turning into a "virtual" pair. The result: renormalized electron charge smaller than bare, Coulomb interaction stronger (0.4% effect)

This effect has been studied in depth in atomic physics, is of particular relevance for exotic atoms where a heavy charged particle replaces an electron in orbit close to the nucleus. Topic close to Walter G Graduate Study work.

Relativistic Quantum Mechanics:
Dirac sea, Klein's paradox, “anti” matter

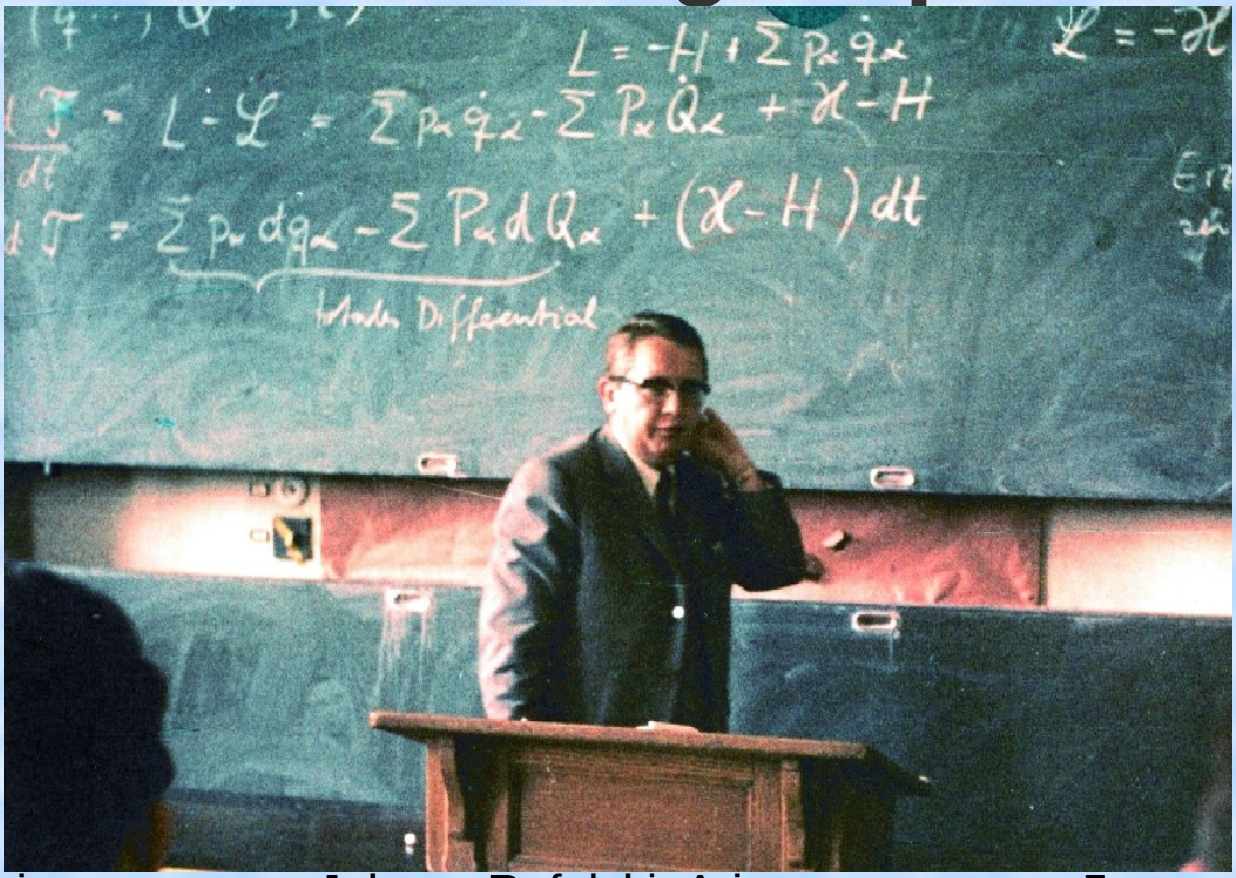


Dirac equation has negative energy states: to stop collapse of matter **Dirac invokes Pauli principle and postulates antimatter:** Positrons are holes in the occupied sea of electrons.

After Klein's “paradox” paper Heisenberg recognizes tunnelling as a new quantum mechanism of pair production. Any electric field is unstable (with a very long lifespan except when fields “bridge” the gap. Nonperturbative quantum field physics ahead of Feynman diagrams. Quantum Aether

***... with the new theory of electrodynamics we are rather forced to have an aether.* – P.A.M. Dirac, ‘Is There an Aether?,’ *Nature*, v.168, 1951, p.906.**

The 1968 revolution: Walter Greiner teaches TH to 1st years, & starts strong fields research group with us



The beggining of WG Era

Literature filled with half-wrong ideas about the meaning of (Oscar) Klein pardox and how to fix the "atom" in strong fields

Sometime around 1965-9 Walter Greiner recognizes the need to understand the atomic structure of superheavy element Z=164

PROCEEDINGS

INTERNATIONAL CONFERENCE
ON PROPERTIES
OF NUCLEAR STATES

MONTREAL, CANADA
AUGUST 25-30, 1969

COMPTES RENDUS

CONFÉRENCE INTERNATIONALE
SUR LES PROPRIÉTÉS
DES ÉTATS NUCLÉAIRES

MONTRÉAL, CANADA
25-30 AOÛT 1969

SESSION 11

PANEL DISCUSSION

SEANCE 11

TABLE RONDE

Chairman/Président: D.H. WILKINSON *(Oxford)*

Scientific Secretary/Secrétaire Scientifique: J.C.D. MILTON *(Chalk River)*

EDITORIAL COMMITTEE/COMITÉ DE PUBLICATION

M. Harvey (Chairman/président)

R. Y. Cusson — J. S. Geiger — J. M. Pearson

held on Saturday morning, August 30
tenue le samedi matin 30 août

Greiner: The important thing is that for Z = 80 you have Zα less than unity, but for super-heavy nuclei around Z = 164 it is suddenly larger than unity and you do not know whether the expansion in Zα converges anymore. You really have to start from a completely different point of view and develop new methods.

Greiner: I would like to stress that this quantum electrodynamic problem is very interesting from a purely theoretical point of view. I mean no matter whether we can make nuclei with Z = 164 or not, it is interesting in itself to study theoretically what really happens. If however elements around Z = 164 were very unstable the problem would be merely academic.

We may ask ourselves what we may further learn from superheavy nuclei. Let me mention a few other important aspects. I certainly do not have to convince you that there is nothing to learn about basic nuclear forces - let's forget this completely.

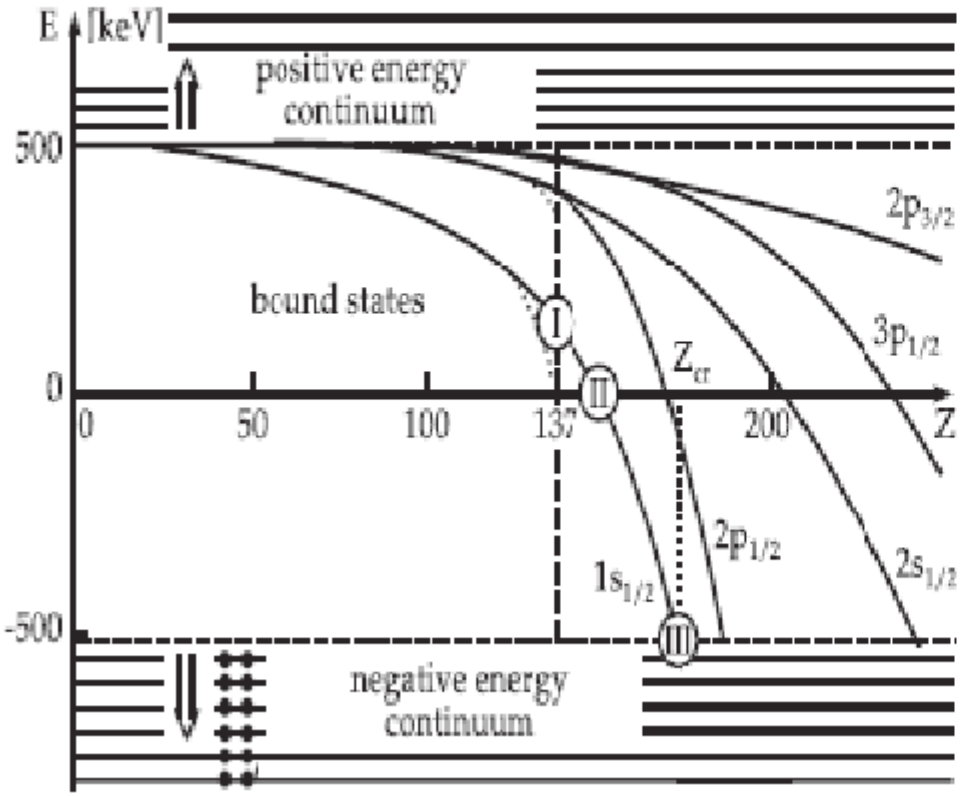
Interior Electron Shells in Superheavy Nuclei

Pieper-Greiner Z. Physik 218, 327-340 (1969)

submitted August 14 1968

1st step: Dirac Singularity solved: finite nuclear size 1965-68 (Pieper-Greiner)

Strong Fields in High Z Atoms



Single Particle Dirac Equation

$$(\vec{\alpha}\cdot i\vec{\nabla}+\beta m+V(r))\Psi_n(\vec{r}) = E_n\Psi_n(\vec{r})$$

$$V(r) = \begin{cases} -\frac{Z\alpha}{r} & r > R_N \\ -\frac{3}{2}\frac{Z\alpha}{R_N} + \frac{r^2}{2}\frac{Z\alpha}{R_N^3} & r < R_N \end{cases}$$

Key feature: bound states pulled from one continuum move as function of $Z\alpha$ across into the other continuum.

2nd step: Walter's great invention

Embedding a super bound electron in positron continuum

VOLUME 28, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1972

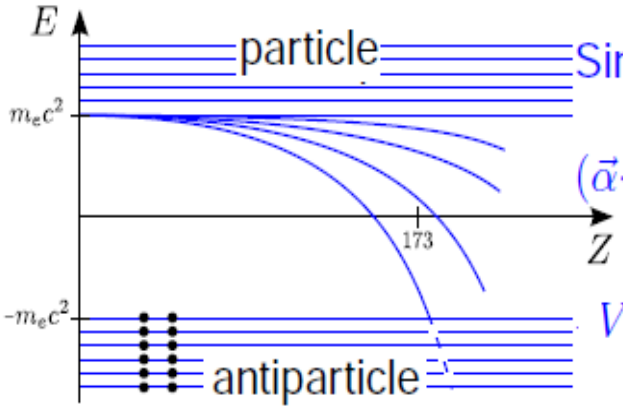
Solution of the Dirac Equation for Strong External Fields*

Berndt Müller, Heinrich Peitz, Johann Rafelski, and Walter Greiner
Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany
(Received 14 February 1972)

The 1*s* bound state of superheavy atoms and molecules reaches a binding energy of $-2mc^2$ at $Z \approx 169$. It is shown that the *K* shell is still localized in r space even beyond this critical proton number and that it has a width Γ (several keV large) which is a positron escape width for ionized *K* shells. The suggestion is made that this effect can be observed in the collision of very heavy ions (superheavy molecules) during the collision.

What is (mostly) this about?

(quasi)Atoms beyond $Z \simeq 100$



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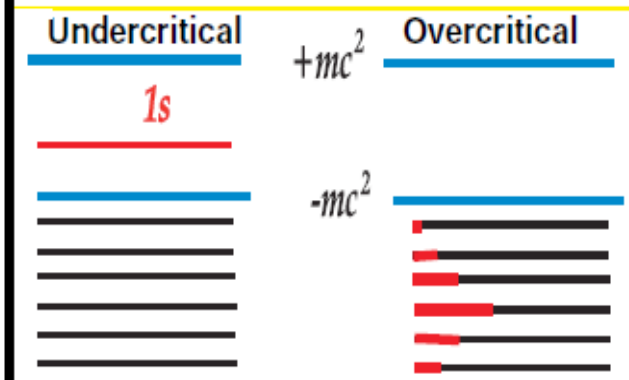
Supercritical fields

The bound states drawn from one continuum move as function of Z across into the other continuum. Mix-up of particle/antiparticle states

Reference: W. Greiner, B. Müller and JR ISBN 3-540-13404-2. "Quantum Electrodynamics of Strong Fields," (Springer Texts and Monographs in Physics, 1985),

Decay of the Vacuum



If diving state 'empty' vacuum decays

$|Q=0\rangle \rightarrow |Q=e\rangle + e^+$ by positron

state occupied by an electron, 'smooth' transition of charge distribution

3rd step: HI Collisions replace the need for super-super-heavy nuclei

HI collisions: electrons in quasimolecuar fields

LETTERE AL NUOVO CIMENTO VOL. 4, N. 11 15 Luglio 1972

Superheavy Electronic Molecules (*).

J. RAFELSKI, B. MÜLLER and W. GREINER

Institut für Theoretische Physik der Universität Frankfurt - Frankfurt/Main

ricevuto il 30 Marzo 1972)

SUPERHEAVY ELECTRONIC MOLECULES

During the last years much work has been done to predict physical [1,2] and chemical [3] properties of superheavy nuclei. Heavy-ion accelerators are under construction [4] so that very heavy-ion collisions above the Coulomb barrier can be carried out in the near future. It is expected that superheavy nuclei will emerge as the end products of these experiments. Also, recently it has been pointed out [5] that another very fundamental aspect of physics can possibly be investigated in these experiments. The formation of superheavy compound nuclei—if existing longer than 10^{-16} s—will

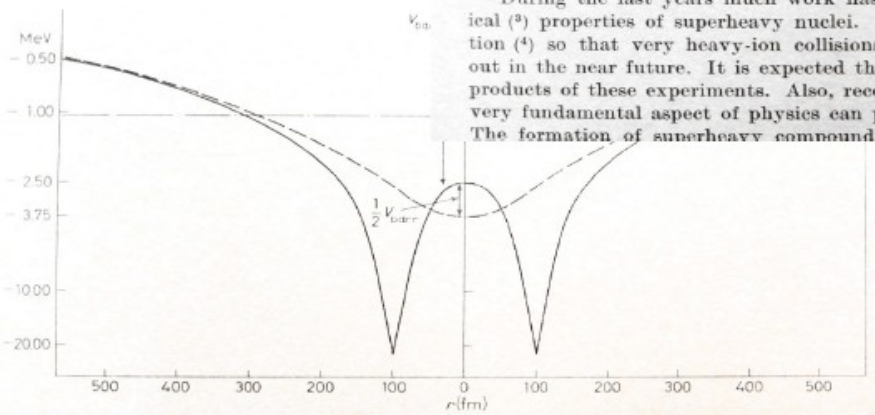
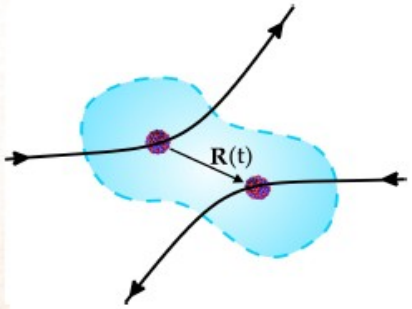


Fig. 2. – The two-centre Coulomb potential is shown for two lead nuclei separated by 200 fm. The dashed curve corresponds to the monopol approximation used in the present numerical calculation of the « molecular » energy eigenvalues. $2 \times Z = 82$, ——— two-centre potential, – – – potential of monopol approximation.



4th and 5th step: no stable vacuum, hence vacuum decay in Strong Fields

IL NUOVO CIMENTO Vol. 13 B, N. 1 11 Gennaio 1973

Superheavy Elements and Nonlinear Electrodynamics (*).

J. Rafelski and W. Greiner
Institut für Theoretische Physik der Universität Frankfurt/Main - Frankfurt/Main

L. P. Fulcher (**)
Institut für Theoretische Physik der Universität Frankfurt/Main - Frankfurt/Main
Department of Physics and Astronomy, University of Maryland - College Park, Md. (***)

(ricevuto il 5 Aprile 1972)

Summary. — Maxwell's equations, which underlie electrodynamics, are linear equations. Nonlinear effects, such as photon-photon scattering, are known to arise in quantum electrodynamics, and one might expect them to become important in the case of strong external fields. We investigate the consequences of a class of nonlinear Lagrangians, which includes that of Born and Infeld and whose common property is that they lead to upper limits for the electric-field strength (somewhat analogous to the upper limit for the velocity of a particle in special relativity). These nonlinear Lagrangians also lead to a finite electromagnetic self-energy for the electron, unlike the case of Maxwellian electrodynamics. The importance of nonlinear effects of course depends upon the size of the upper limit to the electric-field strength. If this upper limit is determined by requiring that the mass of the electron is of an entirely electromagnetic origin, nonlinear effects become very important in determining the eigenvalues of electrons bound to superheavy nuclei. For example, the 1*s* energy eigenvalue is raised by 270 keV for $Z=164$. The Lagrangians considered here do not lead to an absolute gap between bound states and the states of the lower continuum; the 1*s* energy eigenvalue becomes equal to -0.511 MeV, where the lower continuum begins, for $Z=215$. An analogy between nonlinear electrodynamics and higher-order vacuum polarization corrections is studied.

(*) Work supported in part by the Deutsche Forschungsgemeinschaft, by the Bundesministerium für Bildung und Wissenschaft and by the U.S. Atomic Energy Commission.
(**) Fellow of the Alexander von Humboldt-Stiftung.
(***) Present address.

Nuclear Physics B68 (1974) 585–604. North-Holland Publishing Company

THE CHARGED VACUUM IN OVER-CRITICAL FIELDS*

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Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany

Received 4 June 1973
(Revised 17 September 1973)

Abstract: The concept of over-critical fields, i.e. fields in which spontaneous, energy-less electron-position pair creation may occur, is discussed. It is shown that only a charged vacuum can be a stable ground state of the overcritical field. The time-dependent treatment confirms previous results for the cross sections for the auto-ionizing positrons. The questions in connection with the classical Dirac wave functions in over-critical fields are extensively discussed in the frame of the self-consistent formulation of QED including the effects of vacuum polarization and self-energy.

1. Introduction

Over the past years quantum electrodynamics (QED) has been a most successful part of modern field theory, mainly due to achieved agreement between experiment and a power-series expansion of the theory. Whenever in low-energy atomic experiments the external charge Z is larger than one, one has to deal with two expansion parameters, the fine-structure constant α and $Z\alpha$. In very heavy elements we have $Z\alpha \approx 0.7$ and the validity of the power series expansion in $Z\alpha$ should be checked very carefully.

The purpose of this paper is to discuss atomic physics in the case $Z\alpha > 1$. Our starting point will be the exact equations for coupled electron-photon fields. No expansion in $Z\alpha$ will be made. We will use, however, the usual α-expansion, i.e. drop all higher order radiative corrections.

Our main result will be the formal field theoretical rederivation of the previously predicted fact that for Z being larger than a certain value of Z, which we will call $Z_{\text{critical}} \equiv Z_{\text{cr}}$; the vacuum will be charged [1–4]. This fact will lead to a number of observable effects [2, 3, 5], the main one being the spontaneous, energy-less creation of e^+e^- pairs, which has been called "auto-ionization of positrons". An atom with a filled K-shell can only be described by a charged vacuum which can be understood as the K-shell being inbedded into the vacuum for $Z > Z_{\text{cr}}$.

As Z_{cr} is known to be approximately 172 (see refs. [1, 6, 7]) the experimental situation discussed here can be only reached in collisions of very heavy ions, say uranium

* This work has been supported by the Deutsche Forschungsgemeinschaft, by the Bundesministerium für Forschung und Technologie and by the Gesellschaft für Schwerionenforschung (GSI).

The last step 1973: Ffm Rathaus

Accelerated Vacuum – compare

accelerated observer and BH

Back in Frankfurt Summer 1977
Recognize external fields as a
TEMPERATURE

Volume 63A, number 3 PHYSICS LETTERS 14 November 1977

INTERPRETATION OF EXTERNAL FIELDS AS TEMPERATURE*

Berndt MÜLLER and Walter GREINER
Institut für Theoretische Physik, Johann Wolfgang Goethe Universität, 6000 Frankfurt am Main, W.-Germany
and
Johann RAFELSKI
Gesellschaft für Schwerionenforschung, 6100 Darmstadt, W.-Germany

Received 5 September 1977

We show that average excitation of the vacuum state in the presence of an external electric field can be described by an effective temperature $kT = eE/(2\pi m)$. We present a qualitative generalization of our result to other interactions. Some phenomenological implications concerning matter at low temperatures in strong electric fields (10^5 V/cm) are offered.

A stimulating Frankfurt environment 1979-1983

Return to Frankfurt: Introduction of Quark-Gluon Plasma:

QCD vacuum and strangeness arrive

QUARKMATTER--NUCLEAR MATTER

The fusion of constituents of protons and neutrons -- quarks - to quarkmatter is expected to form a new phase of nuclear matt Based on our recent theoretical work this is expected to occu temperature and density accessible to experimental study.

Fachbereich Physik
der Johann Wolfgang Goethe-Universität Frankfurt am Main

Einladung

zu der öffentlichen Antrittsvorlesung des Herrn
Prof. Dr. Johann Rafelski
über das Thema

„Quarkmaterie – Kernmaterie"

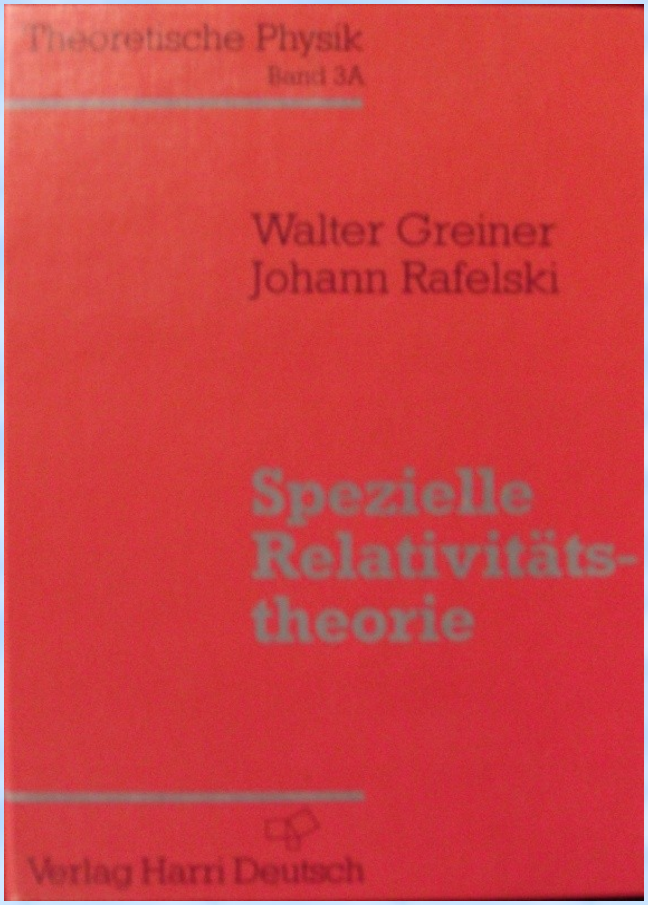
Das Verschmelzen der Bestandteile der Protonen und Neutronen – der Quarks – zur Quarkmaterie, einer neuen Phase der Kernmaterie wird aufgrund von neuesten theoretischen Ar ten in einem experimentell zugänglichen Druck und Temperaturbereich erwartet.

am Mittwoch, dem 18. Juni 1980, 17 Uhr c. t.
im Hörsaal des Instituts für Angewandte Physik
Frankfurt am Main, Robert-Mayer-Straße 2–4

Die Vorlesung findet im Rahmen des Physikalischen Kolloquiums statt.

Der Dekan: Prof. Dr. Werner Martienssen

Joint Project
Book on Special Relativity 1982



Prof. Dr. rer. nat. Walter Greiner, geb. Oktober 1935, Promotion 1961 in Freiburg/Brsg., 1962—1964 Ass. Prof. University of Maryland, seit 1964/65 o. Prof. für Theoretische Physik der Universität Frankfurt am Main und Direktor des Instituts für Theoretische Physik. Gastprofessor u. a. an der Florida State University, University of Virginia, Los Alamos Scientific Laboratory, University of California, Berkeley, Oak Ridge National Laboratory, University of Melbourne, Yale University, Vanderbilt University. Hauptarbeitsgebiete: Theoretische Kernphysik, Theoretische Schwerionenphysik, Feldtheorie (Quantenelektrodynamik, Theorie der Gravitation), Atomphysik. 1974 Empfänger des Max-Born-Preises und der Max-Born-Medaille (Institute of Physics und Deutsche Physikalische Gesellschaft), 1982 des Otto-Hahn-Preises der Stadt Frankfurt am Main und der Ehrendoktorwürde der University of Witwatersrand, Johannesburg.

Dr. Johann Rafelski ist Professor für Theoretische Physik an der Universität Kapstadt. Er promovierte 1973 mit einer Arbeit über Quantenelektrodynamik der starken Felder an der Johann-Wolfgang-Goethe-Universität Frankfurt/Main. Er war wissenschaftlicher Assistent an den Universitäten Frankfurt/Main und Pennsylvania; Wissenschaftler am Argonne National Laboratory, Chicago; Fellow beim CERN, Genève, sowie Professor an der Universität Frankfurt/Main. Der Schwerpunkt der heutigen Forschungsaktivitäten liegt in dem Sub-Nukleonen-Bereich der starken Wechselwirkung. Herr Rafelski hat über 100 wissenschaftliche Arbeiten mitverfaßt, darunter einige längere wissenschaftliche Monographien.

With Walter's strong support I become 1983/4 Chair of Theoretical Physics at the University of Cape Town

Serious differences develop soon:

I turn most energy to quark gluon plasma, a novel strong field domain/vacuum structure;

Some Frankfurt students dared to graduate in Cape Town

I appointed people both who are not educated in Frankfurt,and without asking permission!

We complete our second book 1983-86

QED of Strong Fields Book: 1986

W. Greiner B. Müller J. Rafelski

Quantum Electrodynamics of Strong Fields

With an Introduction into
Modern Relativistic Quantum Mechanics

With 258 Figures

Springer-Verlag
Berlin Heidelberg New York Tokyo

1. Introduction

The structure of the vacuum is one of the most important topics in modern theoretical physics. In the best understood field theory, Quantum Electrodynamics (QED), a transition from the neutral to a charged vacuum in the presence of strong external electromagnetic fields is predicted. This transition is signalled by the occurrence of spontaneous e^+e^- pair creation. The theoretical implications of this process as well as recent successful attempts to verify it experimentally using heavy ion collisions are discussed. A short account of the history of the vacuum concept is given. The role of the vacuum in various areas of physics, like gravitation theory and strong interaction physics is reviewed.

1.1 The Charged Vacuum

Our ability to calculate and predict the behaviour of charged particles in weak electromagnetic fields is primarily due to the relative smallness of the fine-structure constant $\alpha \approx 1/137$. However, physical situations exist in which the coupling constant becomes large, e.g. an atomic nucleus with Z protons can exercise a much stronger electromagnetic force on the surrounding electrons than could be described in perturbation theory, and hence it is foreseeable that the new expansion parameter $(Z\alpha)$ can quite easily be of the order of unity. In such cases non-perturbative methods have to be used to describe the resultant new phenomena, of which the most outstanding is the massive change of the ground-state structure, i.e. of the vacuum of quantum electrodynamics.

Job accomplished: Visby 1986

Tuccson, about 1988

Peniscola 1992

2006: Walter at SQM
QGP and strangeness signature

A dear friend remembered: Michael Danos (picture 1995)

To Walter Greiner on his 80th Birthday