The Universe in the Laboratory

17 March 2016

Electron and its mass

Seminář ELI Beamlines **Čtvrtek, 17.03.2016 14:00 - 16:00**

Přednášející: Prof. Johann Rafelski (*The University of Arizona USA, Department of Physics*)
Místo: Přednáškový sál ELI, Za Radnicí 835 252 41 Dolní Břežany
Jazyk: anglicky
Pořadatelé: **Sekce realizace projektu ELI Beamlines**

Abstract

Electron is the most enigmatic of all elementary particles due to its very small mass that defies understanding for more than a century. In this lecture I will address the theories of the electron mass from historical perspective, leading to the understanding that there must at least two phenomena, the Higgs coupling (material mass) and the electromagnetic field (field mass) that contribute. I will describe the physics phenomena in the early Universe only seconds and minutes after the big-bang that constrain electron mass value in this early stage and at high temperature. I will pose the question how we can use laser-electron interaction to further the understanding of electron mass.

Motivation

A-TEEM: The Science Case

Author/editor: Johann Rafelski

Submitted by: Faculty of Nuclear Sciences and Physical Engineering of Czech Technical University in Prague

Abstract. This document summarizes the transformative research to be developed by the Advanced Theoretical and Experimental Extreme Matter (A-TEEM) in the period 2016-23. Johann Rafelski, the key foreign researcher (KFR) proposes a synergy at the interdisciplinary boundary of present day fundamental knowledge.

A-TEEM addresses extreme elementary forces and their impact on properties of matter under extreme conditions. A-TEEM participates in, and relies on experimental work performed at: European Infrastructure ELI-Beamlines near Prague; and the European laboratory for fundamental physics (CERN) where extreme states of matter are formed in nuclear, particle and extreme light interactions. Our primary objective is deepening the understanding of the fundamental laws of physics governing behavior of elementary particles under extreme force conditions beyond present day reach, with direct impact on current conceptual questions: What is inertia? What is dark energy? What is the meaning of quantum physics and the structure of quantum vacuum state? The tools needed by A-TEEM help advance technologies governing intense radiation environment, interaction of relativistic charged particles with matter, laser-matter interaction, and laser driven nuclear reactions.

This complete research program document includes in consideration of the interdisciplinary context introductory material to facilitate cross-field communication.

Topics today: (also from the forthcoming book: “Relativity Matters”)

Classical Electron, Relativistic Quantum Electron,
QFT & Electron, Cosmology & Electron

Introduction

Many reasons to write this book

More than one hundred and fifty years ago, what we now call special relativity (SR) became a part of our scientific context. To be specific, in a letter dated 5th of January 1865, James Clerk Maxwell wrote to his cousin about his latest scientific work[3]: *I have also a paper afloat containing an electromagnetic theory of light, which, till I am convinced to the contrary, I hold to be great guns.* Maxwell completed a theory that unified what were, at the time, three fundamental phenomena in physics: electricity, magnetism, and light. The unified theory of Maxwell opened the door to relativity, because it is inconsistent with Galilean transformations. In order to describe moving charges as well as charges at rest one needs the Lorentz coordinate transformations of special relativity. This challenge together with theories of the carrier of light waves, the (presumed before Einstein material) æther challenged the greatest minds of physics for nearly the four decades that followed Maxwell's theory; that is, till Einstein's paper of mid-1905.

Einstein finds the solution to the riddle by formulating SR. His paper is accordingly titled[4]: “On the electrodynamics of moving bodies”. Today, the classroom experience with SR begins with Einstein's derivation of what became known as the Lorentz coordinate transformation. Einstein presented the $E = mc^2$ argument a few months later[5]: “Does the inertia of a body depend upon its energy content” – and for many students of science this formula is also where the teaching of and about SR ends. However, students often find the subject of sufficient importance to seek a greater understanding on their own. Much of this book is written for them, in an effort to explain relativity using several communication methods, in order to limit the misunderstanding of concepts, and taking the presentation to the present day level of insight and experimental verification.

Both the principles and the applications of SR constitute today a vast and a subtle topic. This is particularly the case when we strive to comprehend what happens to extended material bodies. It is in this context that the Lorentz-Fitzgerald body contraction emerges as a pivotal concept. But what is contracted? When posing this question I am told most often that space is contracted. This is a blatantly wrong answer. That is why in this book I aim to say ‘body contraction’ as often as it makes good sense in the context. It is hard to understand how and where in popular and/or introductory literature this point of view, ‘space is contracted’, became the norm. Perhaps some confusion with the Lorentz transformation (LT) crept in. LT describes the reference frame transformation and

[3] F. Everitt, “James Clerk Maxwell: a force for physics,” *Physics World* **19** (12) 32 2006)
[4] A. Einstein, “Zur Elektrodynamik bewegter Körper”, Annalen der Physik **17** 891 (1905); received by publishers on June 30, 1905.
[5] A. Einstein, “Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?” , Annalen

Maxwell: energy in the EM field distributed in space

$$H = \int d^3x \left[\frac{1}{8\pi} (\vec{\mathcal{E}}^2 + \vec{\mathcal{B}}^2) - \frac{1}{c} \vec{J} \cdot \vec{A} \right] .$$

$$\vec{\mathcal{E}} = \vec{\mathcal{E}}_\perp + \vec{\mathcal{E}}_c \ \text{ with} \vec{\nabla} \cdot \vec{\mathcal{E}}_\perp = 0, \ \vec{\nabla} \times \vec{\mathcal{E}}_c = 0 .$$

In H no charge source! Coulomb field energy contributes to mass of a charged particle. Physical reality: Coulomb field $\vec{\mathcal{E}}_c$ is delocalized over the large volume.

$$\boxed{m^{\mathrm{C}} c^2 \equiv \frac{1}{8\pi} \int d^3x \, \vec{\mathcal{E}}_c^2} \rightarrow \frac{1}{8\pi} \int \int d^3x' d^3x \, \rho(x') \frac{1}{|\vec{x}' - \vec{x}|} \rho(x) .$$

Mathematical convenience: Use the dynamical equations e.g. insertion of the solution to $\vec{\nabla} \cdot \vec{\mathcal{E}}_c = 4\pi\rho$ for $\vec{\mathcal{E}}_c$ to ‘localize ’ the Coulomb energy content.

EM field mass magnitude verified for the case of atomic nuclei

$$\delta M_A^{\mathrm{EM-field}} = 0.691 \frac{\mathrm{MeV}}{c^2} \underbrace{\frac{Z(Z-1)}{A^{1/3}}}_{R_A \simeq 1.12\ \mathrm{fm} A^{1/3}} .$$

- Characteristic Z, A dependence helps understand nuclear masses.
- Large $c^2 \delta M({}^{82}_{208}\mathrm{Pb}) = 776\,\mathrm{MeV} \simeq \mathcal{O}(m_N c^2)$
- $\delta M_A^{\mathrm{EM-field}} \propto Z^2$ overwhelms for large Z the nuclear binding scaling with A, stability limit for massive atomic nuclei
- $Z^2 - Z$ since we the EM contribution to proton mass incorporated into definition of m_p.

Field energy mass unit charge: Begin with proton

A proton can be localized in space with precision

$$\Delta r = \frac{\hbar c}{m_p c^2} = 0.21\,\mathrm{fm} < R_p \simeq 0.85\,\mathrm{fm}$$

OK to evaluate field energy: we take homogeneous charged sphere of radius R

$$e\mathcal{E}^r_< = \frac{Z^2\alpha\hbar c}{R^2}\,\frac{r}{R}\,, \qquad \mathcal{E}^r_> = \frac{Z^2\alpha\hbar c}{r^2}\,.$$

The two contributions, from within the charge sphere ($r < R$) and from outside ($r > R$) the charge distribution are

$$m^{\mathrm{C}}c^2 = \frac{Z^2\alpha\hbar c}{2R}\left[\left(\frac{1}{5}\right)_< + 1_>\right] = 0.165\,\mathrm{MeV} + 0.825\,\mathrm{MeV}\,.$$

Magnetic, and quark mass effects also contribute such that the proton is slightly lighter $\delta(m_p - m_n)c^2 = -1.293\,$MeV compared to its charge neutral sibling, the neutron.

In Maxwell Electromagnetism field mass divergent for $r \to 0$

$$m^{\mathrm{C}} c^2 \equiv \frac{1}{8\pi} \int d^3x\, \vec{\mathcal{E}}_c^{\,2} = \frac{\alpha\hbar c}{8\pi} 4\pi \int_{r_0/2}^{\infty} dr\, r^2\, \frac{1}{r^4} = \frac{1.4\,\mathrm{MeV\,fm}}{r_0}$$

origin of problem: for small r_0 $\mathcal{E}_r \to \infty$ Solution proposed by M. Born: limiting field (that is limiting force, limiting acceleration) theory. Vacuum is to be a medium such that

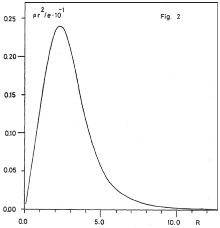
$$\vec{\nabla} \cdot \vec{D} = 4\pi\rho \to D_r = \frac{Z\alpha\hbar c}{r^2} \to \mathcal{E}_r = \frac{\mathcal{D}_r}{\sqrt{1 + \mathcal{D}_r^2 / E_{\mathrm{BI}}^2}}$$

Very elegant reformulation into Born-Infeld nonlinear EM:

$$\mathcal{I}_F = -\int d^4x \sqrt{-\det\, g}\, \frac{\mathcal{E}^2 - \mathcal{B}^2}{2} \;\to\; -\int d^4x \left(\sqrt{-\det\, G} - \sqrt{-\det\, g} \right) E_{\mathrm{BI}}^2$$

$$G_{\mu\nu} = \underbrace{g_{\mu\nu}}_{\text{symmetric}} + \underbrace{F_{\mu\nu}/E_{\mathrm{BI}}}_{\text{antisymmetric}}, \qquad \det\left(G_{\mu\nu}\right) = -1 + \frac{\mathcal{E}^2 - \mathcal{B}^2}{E_{\mathrm{BI}}^2} + \frac{(\mathcal{E} \cdot \mathcal{B})^2}{E_{\mathrm{BI}}^4}$$

...This is also my humble beginning



Die Konsequenzen nichtlinearer elektromagnetischer Feldtheorie in überschweren Elementen

DIPLOMARBEIT

von

Johann Rafelski

aus

Krakau

Institut für Theoretische Physik der Universität

Frankfurt am Main

Juni 1971

INHALTSVERZEICHNIS

COMPARE TO EXPERIMENTS AND SET LIMIT ON $E_{\rm BI}$ PARAMETER

Going for EM electron mass: No GO

958 VOLUME 27, NUMBER 14 PHYSICAL REVIEW LETTERS 4 OCTOBER 1971

Superheavy Elements and an Upper Limit to the Electric Field Strength*

Johann Rafelski, Lewis P. Fulcher,† and Walter Greiner
Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany
(Received 9 August 1971)

An upper limit to the electric field strength, such as that of the nonlinear electrodynamics of Born and Infeld, leads to dramatic differences in the energy eigenvalues and wave functions of atomic electrons bound to superheavy nuclei. For example, the $1s_{1/2}$ energy level joins the lower continuum at $Z=215$ instead of $Z=174$, the value obtained when Maxwell's equations are used to determine the electric field.

IL NUOVO CIMENTO VOL. 7 B, N. 1 11 Gennaio 1972

A Condition for Vanishing Electromagnetic Self-Stress in Nonlinear Classical Electrodynamics (*).

(ricevuto il 26 Luglio 1971)

J. RAFELSKI, L. P. FULCHER (**) and W. GREINER
Institut für Theoretische Physik der Universität Frankfurt - Frankfurt/Main

Summary. — A condition for a vanishing electromagnetic self-stress is established, which also leads to a finite electromagnetic self-energy. Maxwell's theory does not satisfy this requirement. A class of nonlinear theories, which includes that of Born and Infeld, satisfies the condition.

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

Superheavy Elements and Nonlinear Electrodynamics

J. RAFELSKI W. GREINER and L. P. FULCHER (**)
Institut für Theoretische Physik der Universität 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 deter-

PHYSICAL REVIEW A VOLUME 7, NUMBER 3 MARCH 1973

Lower Bound to Limiting Fields in Nonlinear Electrodynamics*

Gerhard Soff, Johann Rafelski, and Walter Greiner
Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany
(Received 31 August 1972)

In view of new high-precision experiments in atomic physics it seems necessary to reexamine nonlinear theories of electrodynamics. The precise calculation of electronic and muonic atomic energies has been used to determine the possible size of the upper limit $E_{\max}$ to the electric field strength, which has been assumed to be a parameter. This is opposed to Born's idea of a purely electromagnetic origin of the electron's mass which determines $E_{\max}$. We find $E_{\max} \geq 1.7\times 10^{20}$ V/cm.

COMPARE TO EXPERIMENTS AND SET LIMIT ON $E_{\rm BI}$ PARAMETER

1928/29: Beginning of a new scientific epoch

- 1928 Dirac invents the 'Dirac' equation

$$(E - V)\Psi = \vec{\alpha}\cdot(-i\hbar\vec{\nabla} - e\vec{A})\Psi + \beta m\Psi$$

- 1929 Oscar Klein and Yoshio Nishina compute the relativistic 'Compton effect' cross section

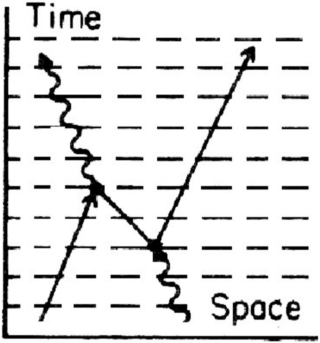
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\frac{\lambda^2}{\lambda'^2}\left(\frac{\lambda}{\lambda'} + \frac{\lambda'}{\lambda} - 2\sin^2\theta\,\cos^2\phi\right)\ ,$$

- $\gamma e \to \gamma e$ has in long wave length (Thompson) limit the total integrated cross section

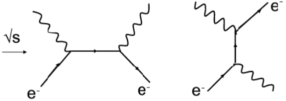
$$\sigma = 665\,\mathrm{mb} = \frac{8\pi}{3}r_0^2\ , \qquad r_0 = \frac{386\ \mathrm{fm}}{137} = 2.82\ \mathrm{fm}$$

The 'point electron' in scattering presents itself much bigger than the strongly interacting proton. Electron is a point particle that is really not a point at all!

Old vs New: time evolution vs CPT



virtual electron-positron pair is produced and later annihilated. This suggests electron is big because of pair fluctuation in the vacuum. Introduction of Feynman diagrams looses the deep insight that accompanied the early interpretation of KN computation.



Compton scattering

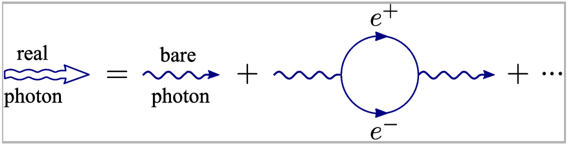
In Feynman language

Non-canceling contribution to KN scattering

Classical Thompson computation of electron-photon interaction appears meaningless

After KN

- Vacuum is polarizable: e^+e^- vacuum polarization effect screens charge (renormalization) and balance acts to increase the strength of the potential of a charge at short distances. (E.A.Uehling, 1935);



- Plane waves travel in vacuum uninhibited. (J. Schwinger 1951)

How come vacuum is not opaque given all these virtual pairs and huge KN cross section?

GAUGE INVARIANCE AND VACUUM POLARIZATION

We can conclude, without further calculation, that the physical quantities characterizing the plane wave field, the components of the energy-momentum tensor $T_{\mu\nu}$, will be identical in form with those of a constant field that obeys Eq. (4.34). On referring to Eq. (3.57), we see that $T_{\mu\nu}$ for a plane wave is just that of the maxwell field, which may be simplified further to

$$T_{\mu\nu} = F_{\mu\lambda}F_{\nu\lambda} = n_\mu n_\nu F^2(\xi). \qquad (4.35)$$

Thus, there are no nonlinear vacuum phenomena for a single plane wave, of arbitrary strength and spectral composition.

672 JULIAN SCHWINGER

IS MASS OF ELECTRON ELECTROMAGNETIC?

- Lambshift: A surprise that was not expected: allows to probe how electron interacts with a photon at its location.
After introducing mass counter term and renormalizing the electron mass, QED-Feynman framework provides computational capability, at a prize (renormalizability in QED (Harvard Lecture III-7)) !

$$iG^{\rm bare}(\not p) = \frac{i}{\not p - m_0 + \Sigma_2(\not p) + \cdots}$$

From the bare Green's function compute the renormalized Green's function as

$$iG^R(\not p) = \frac{1}{1+\delta_2} iG^{\rm bare}(\not p) = \cdot = \frac{i}{\not p - m_0 + \delta_2 \not p - m_0\delta_2 + \Sigma_2(\not p) + \cdots}$$

where the $\cdots$ are formally $\mathcal{O}(e^4)$ or higher. Then $m_0 = m_R + m_R\delta_m$,

$$iG^R(\not p) = \frac{i}{\not p - m_R + \delta_2 \not p - (\delta_2+\delta_m)m_R + \Sigma_2(\not p) + \cdots} = \frac{i}{\not p - m_R + \Sigma_R(\not p)}$$

with $\Sigma_R(\not p) = \Sigma_2(\not p) + \delta_2\not p - (\delta_m + \delta_2)m_R + \mathcal{O}(e^4)$. To justify such treatment rewrite the bare free Lagrangian in terms of renormalized fields

$$\mathcal{L} = i\bar\psi^0 \not\partial \psi^0 - m_0\bar\psi^0\psi^0 = i\, Z_2 \bar\psi^R \not\partial \psi^R - Z_2 Z_m m_R \bar\psi^R\psi^R$$

using Eqs. (19) and (20) this becomes

$$\mathcal{L} = i\,\bar\psi^R \not\partial \psi^R - m^R\bar\psi^R\psi^R + i\delta_2\bar\psi^R\not\partial\psi^R - m_R(\delta_2+\delta_m)\bar\psi^R\psi^R$$

Higgs mass of particles

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

G. Zweig ×)
CERN – Geneva

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space–time

A schematic model of baryons and mesons

M. Gell-Mann

California Institute of Technology, Pasadena, California, USA

Received 4 January 1964,

Physics Letters

Volume 8, Issue 3,

1 February 1964, Pages 214–215

Nearly 50 years after its prediction, particle physicists have finally captured the Higgs boson.

Mass

Broken Symmetries and the Masses of Gauge Bosons

Peter W. Higgs

Phys. Rev. Lett. 13, 508 (1964)

Published October 19, 1964

Broken Symmetry and the Mass of Gauge Vector Mesons

F. Englert and R. Brout

Phys. Rev. Lett. 13, 321 (1964)

Published August 31, 1964

MASS OF ELECTRON

- EM mass in the field (as described) $\mathcal{O}(1-3)$ MeV
- Higgs 'material' mass due to 'minimal' coupling

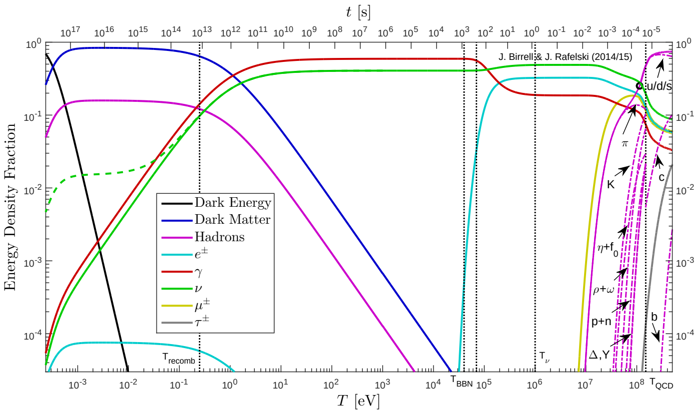
$$\mathcal{L} = g_{\mathrm{H-e}}\phi\bar{\Psi}\Psi\ , \qquad g_{\mathrm{H-e}} = \frac{\sqrt{2}0.511\ \mathrm{MeV}}{246\mathrm{GeV}} = 2.94\ 10^{-6}$$

Coupling exceedingly weak.

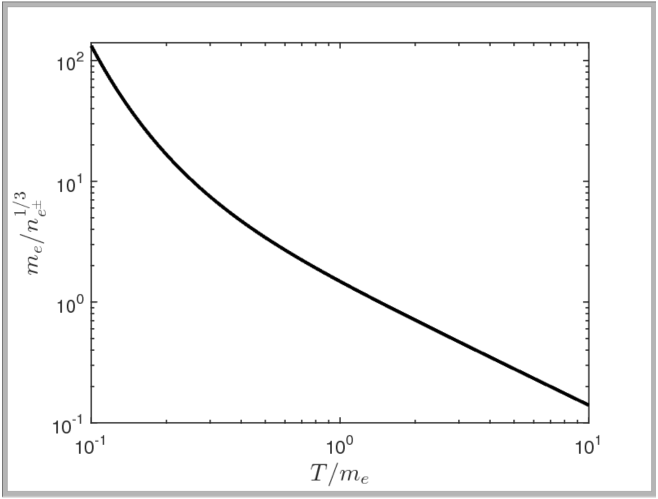
- EM acceleration attaches to electron charge but how does this play out with two mass components?
- What if mass contributions are large and difference is small?

OTHER INFORMATION ON ELECTRON MASS

Once upon a time: Universe filled with a dense electron plasma at a temperature T a few MeV.



Dense Packed Electrons and Positrons in the Early Universe



Reheating

Once a family ‘i’ of particles decouples at a photon temperature of T_i, a difference in its temperature from that of photons will build up during subsequent reheating periods as other particles feed their entropy into photons. This leads to a temperature ratio at $T_\gamma < T_i$ of

$$R \equiv T_i/T_\gamma = \left(\frac{g_*^S(T_\gamma)}{g_*^S(T_i)}\right)^{1/3} .$$

This determines the present day reheating ratio as a function of decoupling temperature T_i throughout the Universe history.
Example: neutrinos colder compared to photons.
Reheating ‘hides’ early freezing particles: darkness

Reheating History

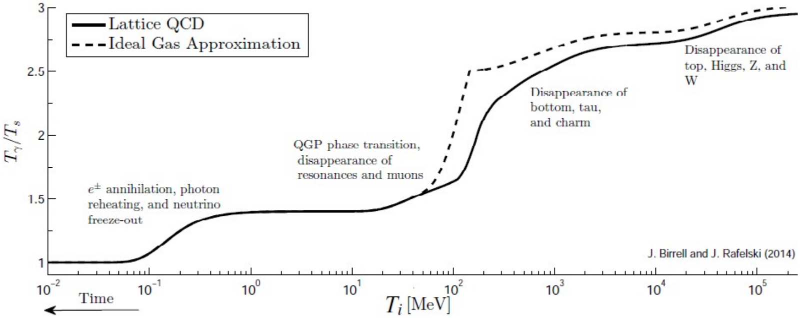


Figure: The reheating ratio reflects the disappearance of degrees of freedom from the Universe as function of T_i. These results are for adiabatic evolution of the Universe. Primordial dark matter colder by factor 3. Particles decouple at QGP hadronization colder by factor 2.

Neutrino count as an observable

The sp[eed of expansion of Universe fine tuned to produce fluctuations in CMB. This sets limit on how much energy neutrinos can carry pushing the Universe apart. It so happens that electron mass directly impacts this.

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Nuclear Physics B 890 (2015) 481–517
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Relic neutrino freeze-out: Dependence on naturalconstants

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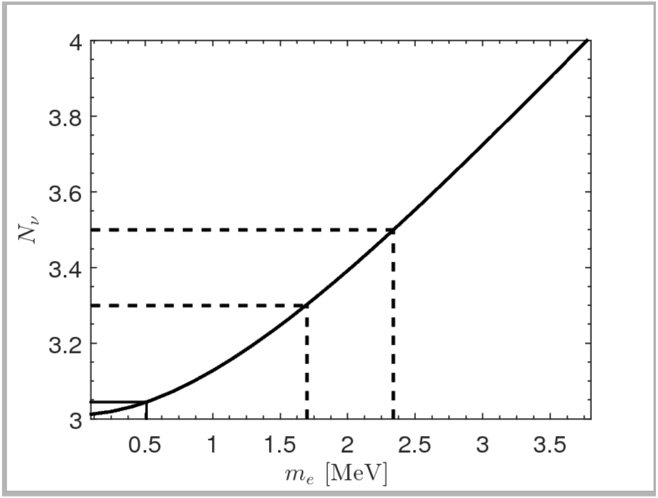
Received 9 June 2014; received in revised form 2 November 2014; accepted 22 November 2014
Available online 27 November 2014
Editor: Tommy Ohlsson

Abstract

Analysis of cosmic microwave background radiation fluctuations favors an effective number of neutrinos, $N_\nu > 3$. This motivates a reinvestigation of the neutrino freeze-out process. Here we characterize the dependence of N_ν on the Standard Model (SM) parameters that govern neutrino freeze-out. We show that N_ν depends on a combination η of several natural constants characterizing the relative strength of weak interaction processes in the early Universe and on the Weinberg angle $\sin^2\theta_W$. We determine numerically the dependence $N_\nu(\eta, \sin^2\theta_W)$ and discuss these results. The extensive numerical computations are made possible by two novel numerical procedures: a spectral method Boltzmann equation solver adapted to allow for strong reheating and emergent chemical non-equilibrium, and a method to evaluate Boltzmann equation collision integrals that generates a smooth integrand.

Observable neutrino reheating as function of electron mass



CONCLUSIONS

Unpredictable insight into connection of electrons masses and charge awaits discovery