Properties of Fractons

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Abstract

The theoretical origin of fractionally-charged particles, as well as the pertinent experimental verifications, are exposed.
So-called fractons are fractionally-charged-particles which arise in several models.
The different types of fractons can be Hadronic-matter fractons, which be resulting in the description of new-long-range interactions, and leptonic fractons, which can be obtained after several kinds of super-symmetric theories.
The attestation of the existence of fractons is looked for in Early Cosmology, Cosmology and Astrophysics.
The postulation of the existence of fractons after the description of new long-range forces is recalled.
Group-theoretical examinations are scrutinised.
Particle-recombination modes are analysed.
Experimental searches are enumerated.

Summary

- Search for new long-range forces.

- Fractons:
  - Types of Fractons;
  - Fractons from supersymmetric theories.

- Experimental searches for Fractons:
  - accelerator experiments;
  - cosmic-rays experiments;
  - mass-spectrometer experiments;
  - Fractons from Gravity experiments;
  - Further experiments about fractons.

- Particles-recombinations products:
  -theoretical frameworks of recombination products;
  - experimental searches of recombination products.

- Prospective investigations.

Introduction

Fractons can be looked for in Galactical matter, in matter around celestial bodies (i.e. the Sun), in meteoritic matter and within the Earth matter. The main experimental techniques for the search for fractons can consists of accelerator experiments, cosmic-rays experiments, mass-spectrometer experiments, cantilever experiments and experiments involving the gravitational interaction as well

Search for new long-range forces

The G_Y interaction.

Particles:
- standard-model particles ($_o$-particles: photons, gluons, intermediate vector bosons V_o, and quarks and leptons fermions F_o);
- new long-range interaction: $_Y$-particles: gauge fields V_Y, do not interact with the $_o$-particles, F_Y $_Y$ fermions.
- $_x$ particles interacting with both V fields.
- $_o$-particles and $_Y$-particles have the phenomenology of a common gravitational interaction.

Search for $_Y$-matter:
- gravitational radiation from a system of double $_Y$-stars,
- $_Y$-matter near the Sun, $_Y$-spheres in the Earth system.
- Combination of $_x$-matter and $_Y$-matter lead by forces not weaker than those derived by the usual chemical forces:
  - $_Y$-matter on the Earth.

L. B. Okun', On searches for new long-range forces, Zh. Eksp. Teor. Fiz. 52,694-697, 1980.

Fractionally-charged particles

Fractons arise from the unified gauge symmetry group

$$G_{OXY} \equiv G_{W\ \ \_S} \times SU(3)_c + G_Y$$

with

- $G_{W\ \ \_S} = SU(2) \times U(1)$,
- $SU(3)_c$ strong color interaction,
- G_Y Y interaction.

After the breaking of G_Y to G_{Yem} (Y electromagnetism):

- they are X-hadrons produced in hadronic processes after the two-gluons mechanism
$gg \to x\bar{x}$.

M. Yu. Khlopov, Fractionally charged particles and quark confinement, JETP Letters, 33, 162, 1981.

- **hadronic processes at high energies**;

- XXX **hadrons consisting of light** 0**-quark pairs**, the contribution of X quark pairs being negligible;

- Y **hadrons produced from a symmetry group**:
$G_{0XY} \equiv G_{W \quad -S} \times SU(3)_c + G_Y \times G_{Yc}$:
  - **hot phase of the Early Universe**;
  - **lower limit of the quark abundance greater than that for relic quarks**.

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Fractons from Supersymmetric models

fractionally-charged particles (leptons) have been proposed also as a probe for supersymmetric theories.
P. Frampton and T. Kephart, Fractionally Charged Particles as Evidence for Supersymmetry, Phys. Rev. Lett. **49** (1982), 1310.

- after requiring asymptotic freedom, fracton arise in supersymmetric GUT's (or GUT's) in the trivial embeddings of $SU(7)$ in $SU(N)$ and in $O(14)$.

It is not possible for E_6 to produce fractons.

- the related quarks $\tilde{q}$ with charge $q = \frac{1}{3}e$ arise from models of supersymmetric GUT's:
- nontrivial embeddings of $SU(5)$:

- at least one fracton is expected to be absolutely stable (Earth-based experiments on niobium spheres).

G. S. LaRue, J. D. Phillips, and W. M. Fairbank, Observation of fractional charge of (1/3)e on matter Phys. Rev. Lett. 46, 967 (1981).

Astrophysical observation:

- fractons in annihilation processes after the big bang, and on the present observed upper bound on their number density in matter;

- in particular, stable fractons heavy $q = \frac{1}{3}$ leptons could bind to the p H atoms and produce a shift in the spectral lines of the infrared spectra of Population II (i.e., *metalpoor*) stars, with concentrations of one part in 10^8;

H. Goldberg, Fractionally Charged Heavy Leptons: Cosmological Implications of Their Existence, and a Prediction of Their Abundance, Phys. Rev. Lett. 48, 1518 (1982).;

- $\frac{1}{3}e$-charged heavy leptons can annihilate in heavy stars down to an abundance of 10^{-19};

- masses of fractons on order of the mass scale of the breaking of the electroweak group and/or at $50-100 GeV$ to be evaluated in $\bar{p}p$ and e^+e^- experiments.

Electroweak but not strong interations

There exist potentially unconstrained regions of the parameter space in the (Q_L, m_L) plane available for fractons with electroweak interaction in the cosmic rays spectra, with

- Q_L (fractional) electric charge;
- m_L lepton mass.

$\Rightarrow$ Constrains on Q_L are obtained in **accelerator experiments**.
P. Langacker and G. Steigman, Requiem for an FCHAMP? Fractionally Charged, Massive Particle, Phys. Rev. D **84**, 065040 (2011) [arXiv:1107.3131 [hep-ph]].

Metastable quarks of 4-th generation in heavy stable hadrons

- primordial quarks in the Early Universe combining in cosmic Heavy hadrons and annihilating into cosmic rays;

- relic presence in the Universe and Earth-based detection.

K. Belotsky, D. Fargion, M. Khlopov, R. Konoplich, M. Ryskin, K. Shibaev, May heavy hadrons of the 4th generation be hidden in our universe while close to detection?, Gravitation and Cosmology, Vol. 11 (2005), No. 1-2 (41-42) [arXiv:hep-ph/0411271 [hep-ph]].

Two-hadrons recombination experimental searches

- fraction quarks and recombination of two hadrons ($\bar{h}h$)
$\Rightarrow$ can be studied also in quark experiments:

- Accelerators;
- Cosmic rays.

L. Lyons, Quark Search Experiments at Accelerators and in Cosmic Rays, Phys. Rept. **129** (1985), 225.

- *Accelerators experiments*
  - Limits on fractional-charge particle production from stable-matter search techniques:

- Plastic-detector experimens;
- Čerenkov-effect experiments;
- Emulsion experiments (after some symmetry-breaking mechanisms).

- *cosmic-rays experiments*

- primary cosmic ray flux;

- produced after interactions of very highly-energetic cosmic rays with the atmosphere:

cosmic ray telescope 250 m underground, to look for magnetic monopoles or for fractionally-charged particles (measure of the velocities and energy losses for isolated tracks) [**?**]:

nonrelativistic particles $3.5 \cdot 10^{-4} < \beta < 0.4$:
particles with charge $\frac{2}{3}$: $6 \cdot 10^{13}$ *particles* cm^{-2} sr^{-1} s^{-1};
particles with charge $\frac{1}{3}$: $6 \cdot 10^{-4}$ *particles* cm^{-2} sr^{-1} s^{-1};

relativistic particles:
particles with charge $\frac{2}{3}$: $2 \cdot 10^{-12}$ *particles* cm^{-2} sr^{-1} s^{-1}.

- cosmic rays: isolated quarks unaccompanied by other particles processes;

- delayed air showers: delayed hadrons;

- $\frac{4}{3}e$-charged particles detected by drift chambers at zenith angles of 31° to 49° estimated via its energy loss:
flux of $6(4.0 \pm 1.5) \cdot 10^{-9}$ *particles* cm^{-2} sr^{-1} s^{-1};
lack of events for $\frac{1}{3}e$-charged particles 90% and for $\frac{2}{3}e$-charged particles .
T. Wada, Y. Yamashita and I. Yamamoto, Lett. Nuov. Cim. 40 (1984) 329, and related references.

Comparison of cosmic-rays experiments:

L. Lyons, Quark Search Experiments at Accelerators and in Cosmic Rays, Phys. Rept. **129** (1985), 225.

- *Stable matter searches by mass spectrometer*

- residual charges $\frac{1}{3}e$ in steel balls:
at the 90% confidence level, $< 10^{-21}$ quarks per nucleon;
M. Marinelli, G. Morpurgo, Phys. Lett. 137B (1984) 439.

Search for fractons on Earth matter

-for fractons, the resulting nucleosynthesis would be different from that of normal nuclei, i.e.

fractons should be looked for between normal *Na* and heavy *Na* inside the Earth crust, in the manufacture of the *Na* sample used, or in the production of the atomic beam(s).
W.J. Dick, G.W. Greenlees and S.L. Kaufman, Phys. Rev. Lett. 53 (1984) 431.

Fractionally-charged particles in meteors

$< 1.3 \cdot 10^{-21}$ particles per nucleon in meteoritic material;
$< 1.9 \cdot 10^{-23}$ particles per nucleon in meteoritic mineral oil.
P. C. Kim, E. R. Lee, I. T. Lee, M. L. Perl, V. Halyo and D. Loomba, Search for fractional-charge particles in meteoritic material, Phys. Rev. Lett. **99** (2007), 161804.

Upper limits for the gluon mass

After taking into account an upper limit for the gluon mass too, m_g, $m_g < O(1)$ Mev:

- very small in comparison to Λ_{QCD};
- ultraviolet cut-off of Λ_{UV} in QCD with $m_g \neq 0$, considered as an effective field theory, has a very different form from the ultraviolet cut-off in the electroweak theory with heavy Higgs boson(s).

S. Nussinov and R. Shrock, Upper Limits on a Possible Gluon Mass, Phys. Rev. D **82** (2010), 034031.

Cantilever-type experiments

- *Sparticles*

in a weak gravitational field
mass dispersion relation Δm_{ij} for masses m_{ij}

$$\frac{\Delta m_{jk}^2}{m_0^2} = \frac{\lambda_j \lambda_k^*}{\pi^2} \ln \frac{M_{Pl}}{M_G}, \tag{1}$$

- λ_i factorizes the (requested) coupling constant
- m_0 is the mass of the common (standard-model) scalar (normalized to Planck mass M_{Pl})
- M_G is the mass for a (massive) gravitational mode.

- after the breach of higher-dimensional structures, non-perturbative degrees of freedom give rise to Compton-length waves (particles) whose masses M_C are comparable with Planck mass M_{Pl}
- they interact very weakly and gravitationally;
- masses M_C are of order $M_C \simeq R/M_{Pl}$;
  with R the lower bound on the compactification (energy) scale: their gravitational interaction can modify ordinary Newtonian gravity;
- verifications of M_C can be achieved by cantilever detectors and/or silicon-based microelectromechanical systems.

- *Fractional charges*

An instrument aimed at detecting fractional-charge particles is the **rotor electrometer**.

It was designed as a Faraday container with an arbitrary high-impedance amplifier, endowed with copper pads, for which different charges reach the container walls at different velocities, such that the time of flight can be calculated, i.e., after a tuning the impedance suited for the charge to be detected.

J.C. Price, W.R. Innes, S. Klein, M.L. Perl, The rotor electrometer: A new instrument for bulk matter quark search experiments, *Rev. Sci. Instrum.* **1986**, *57*, 2691.

- *Complex orbifolds*

The existence of fractional quantum numbers n has also been postulated for complex orbifolds.

V. Mathai, G. Wilkin, Fractional quantum numbers via complex orbifolds, arXiv:1811.11748.

- *$_x$-partilces in matter and in biological samples*

After a further assumption that
- $_x$-particles should have any kinds of Abelian charges, and
- that the coupling constant to the corresponding V_Y-photonic fields is of the order of α,

$\Rightarrow$ the detection of $_x$-partilces in matter and in biological samples should be analyzed by van der Waals energy scales to fix an upper bound for them, which should improve Cavendish-type experiments by and order 10^{-3}

Gravitational interaction

Possibility of fractionally-charged matter after gravitational interaction:

- from the early development of Active Galactic Nuclei,
reconstruct a continuum image of the nucleus as far as the dust emission is concerned for near-infrared baseline-interferometric data, and
- for the dust-sublimation regions

$\Rightarrow$ any discrepancies from the found data could be reconducted to the presence of fractionally-charged dust matter.

GRAVITY Collaboration, An image of the dust sublimation region in the nucleus of NGC 1068, Astronomy and Astrophysics, 634, A1 (2020).

Lepton annihilation into hadrons and recombination

recombination $\bar{h}h$

Electroweak radiative corrections in (the simplest example) of e^+e^- scattering on the differential cross-section and left/right asymmetries modify the polarization degrees of the initial beams and depend also on the energy.

e^+e^- scattering:
- light-quarks and heavy-quark pair production;
- quarkonium production;
- hadron production through narrow resonance.

J. Fujimoto, M. Igarashi, N. Nakazawa, Y. Shimizu and K. Tobimatsu, Radiative corrections to e^+e^- reactions in electroweak theory, Prog. Theor. Phys. Suppl. **100** (1990), 1-379;
S. Bondarenko, Y. Dydyshka, L. Kalinovskaya, R. Sadykov, V. Yermolchyk, One-loop electroweak radiative corrections to lepton pair production in polarized electron-positron collisions, [arXiv:2005.04748 [hep-ph]].

Search for fractons in baryonic matter

exploration of QCD matter at neutron star core densities (compressed baryonic matter):

- fluctuations;
- event characterization.

P. Senger, Status of the Compressed Baryonic Matter experiment at FAIR, Int. J. Mod. Phys. E **29** (2020), 2030001.

High-energy hadronic processes and quarks quantum numbers

resonance production in proton-proton collisions at $\sqrt{s} = 7\,TeV$ and $\sqrt{s} = 13\,TeV$
($p - p$ collisions and $p - Pb$ LHC):

- hadronization in the partonic phase;
- ratio for baryonic resonances to non-resonance baryons having similar quark content;
- ratios found to be independent of the collision energy of the system.

A. Goswami, R. Nayak, B. K. Nandi and S. Dash, Effect of color reconnection and rope formation on resonance production in p−p collisions in Pythia 8, [arXiv:1911.00559 [hep-ph]].

Anomalous lepton-lepton scattering

Electron-electron scattering and electron-positron scattering at $0.6 - 1.7 MeV$:

- cross-sections at $0.61 MeV$ were significantly smaller than th predicted values;
- departure from quantum electrodynamics;
- possibility for a non-Coulombian central force.

R. Sen, Possible violation of spin-statistics connection in electron-electron scattering at low relativistic energies, [arXiv:2004.14481 [hep-ph]].

Fractional-electric-charged-particles: ab initio derivation, calculations, experimental verifications

Fractional-electric-charged-particles can be due either to a
- broken color symmetry; or to an
- 'enlarged' GUT theory to which color singlets can be included.

$\Rightarrow$ according to these two mechanisms, fractons are expected to acquire $1/3$ electric charge.

In an **unbroken color symmetry**, an $SU(5)$ model which allows for fractons in $S(7)$ non-trivial change of embedding can be considered: such a non-trivial change of embedding consists of
- 2 normal $SU(5)$ families, and
- 2 charge-shifted conjugated families. The latter must be light ($\lesssim 100 GeV$) for them to acquire muss only after the breaking of $SU(2) \otimes U(1)$.

Charge-shifted families contain both fractionally-charged leptons and fractionally-charged quarks, with charges q not in sequence

$$q \equiv (\frac{2}{3} + n),$$

with n integer.

Here, **a fracton can be either a lepton or a hadron**.

a **broken** $SU(7)$

$$SU(7) \to SU(3) \otimes SU(2) \times U(1)$$

- at super-heavy mass scales, is obtained by scalars in the irreps of high dimensionality; and
- cannot couple directly with fermions.

J. Wess and B. Zumino, A Lagrangian Model Invariant Under Supergauge Transformations, Phys. Lett. 49B, 52 (1974).

Given the Lagrangian model L_0

- invariant under supergauge transformations in the one-loop approximation,

$$L_0 = -\frac{1}{2}(\partial_\mu A)^2 - \frac{1}{2}(\partial_\mu B)^2 - \frac{1}{2}i\bar{\psi}\gamma^\mu\partial_\mu\Psi + \frac{1}{2}F^2 + \frac{1}{2}G^2$$

, with A scalar,
B pseudoscalar,
ψ Majorana particle,
F and G auxiliary fields:

$\Rightarrow$ conformal transformations and γ^5 transformations in the algebra imply that only theories with massless particles can be invariant under supergauge transformations:

- possible to eliminate the pertinent commutators and anticommutators

F. A. Berezin and G.I. Katz, Lie groups with commuting and anticommuting parameters, Mathemat. Sbornik (USSR), 82 (1970) 343 [English translation Vol. 11].

differently,

- necessary to restrict to the consequent sub-algebra to
  - remove massless particles, and
  - obtain supergauges with constant parameters.

J. Wess and B. Zumino, A Lagrangian Model Invariant Under Supergauge Transformations, Phys. Lett. 49B, 52 (1974).

Given the invariant Λ

$$\Lambda \equiv \lambda F,$$

the auxiliary fields can be eliminated from the Lagrangean:

$\Rightarrow$ possible to
- study of higher order corrections, and
- construct more complex and more realistic models, invariant under a combination of supergauge and internal symmetries.

Broken colour $SU(3)$

A **broken color** $SU(3)$ implies the presence of
- quarks, and of
- *'diquarks'*.

Observed charges: the color singlet $\underline{1}_c$-particles with fractional charges.

- This implies a kind of GUT of electroweak interactions and strong interactions, which equals to minimal extensions of $SU(5)$ to include fractionally-charged color singlets.

- The model $SU(6)$ does not fit the requirements for such constructions:
- the mixing parameter $\sin^2\theta_w$ implies the presence of many light doublets to be added on purpose.

H. Goldberg, T. W. Kephart, M. T. Vaughn, Fractionally Charged Color-Singlet Fermions in a Grand Unified Theory, Phys. Rev. Lett. 47, 1429 (1981).

Constraints for the obtention of fractons

- **Representation constraints** (R):

in the simplest case

- R_1: fermionic representations $\underline{1}_c$, $\underline{3}_c$, $\underline{1}_c^*$;
- R_2: reducible fermionic representations:
  - complex;
  - flavor-chiral;
  - free of Adler-Bell-Jackiw anomalies;
- R_3: the found representations of the symmetry group must contain at least $\underline{3}_c$ or $\underline{1}_c{}^*$;
- R_4: the sum of the charges of the found representations should equal zero;
- R_5: $\Delta Q = \pm 1$ for weak currents $\Rightarrow \exists$ two $\underline{1}_c$-fields which differ by ± 1.
- R_7: for pure vector couplings of the unbroken $SU_c(3) \otimes U_{em}(1)$ $SU_c(3) \otimes U_{em}(1)$, Weyl fields must be pairs of fermionic representations $\{\ F\}$ with $q \neq 0$.

Dynamical constraints (D)

- D_1: symmetries must break at a mass scale μ, $\mu \simeq 100 Gev$
as
$SU_c(3) \otimes U_{em}(1)$;
- D_2: the spectrum must be such that the GUT is at a mass M, $M \gtrsim 10^{14} GeV$ to avoid proton decay;
  - $\alpha_s(100GeV)$: $0.1 < \alpha_s < 0.3$;
  - $\alpha_M \lesssim 0.3$;
  - the mixing angle θ_w: $\sin^2\theta_w \sim 0.20$.

- By **combining the constrains**, the conditions are obtained:

- R_1, R_2 iff anomaly-free red. repr.'s of $SU(N)$ constructed from irrepr.'s corresponding to single-color Young tables (with all indices desymmetrized);
- R_3, R_5 + request of fractionally-charged color singlets:
  - $SU(6)$ is excluded;
  - $SU(7)$ must contain a vector coupling $SU_c(3) \otimes U_{em}(1)$;

from spinorial representations of $O(14)$.

- Remarks

$Q=\frac{2}{3}$, $Q=-\frac{1}{3}$, $Q=0$ do not violate the R constraints.
$Q=-\frac{1}{3}$, $Q=0$ contain only one generation of ordinary quarks and leptons.
As a result, (the values of the charge(s) of) the possible eigenvalues of the charge operator Q can be assigned. For this purpose,
- three copies of the fermionic representations $\{\ F\}$ are required for the theory to contain the known quarks and leptons;
- all fermions must be light with respect to M;
- Higgs scalars contributing to the fermionic-mass matrix must breaks the weak $SU(2)$ group.

- D_1, D_2: two different predicted values of $\sin^2\theta_w$:
  - non-exotic Dirac fields;
  - exotic Dirac fields.

- *Both*:
  - Q_5's, i.e. $SU(5)$ charge operators, are defined;
  - exotic-charge operators Q_e are conserved;

separately by *any* symmetry-breaking Higgs scalar
(which can be decomposed of two fermions)
for the conservation of the total charge.

Further tentative models 1

The implications of a $SU(5)$ GUT's containing
$SU(3)_c \times SU(2)_L \times U(1)$,
the mixing angle and the proton lifetime have been analyzed
for a single super-heavy mass scale $\tilde{m}_s$ (unification mass scale).
The lifetime of a proton becomes smaller when
superheavy-Higgs-boson-mediated amplitudes become significant (
higher-order amplitudes of effective dimension 5 give rise to proton
life-times proportional to m_s^2 rather than m_s^4.

W.J. Marciano, G. Senjanovic, Predictions of supersymmetric grand unified theories, Phys. Rev. D 25, 3092 (1982).

Further tentative models 2

The experimental value
$\sin^2(\hat{\theta}_W(M_W)) = 0.215 \pm 0.014$
is here confirmed; **the proton results nevertheless unstable**.
In order to increase the lifetime of the proton, supersymmetric constraints have to be imposed; such constraints require N_H relatively light weak isodoublets and n_g generations of quarks and leptons for the pertinent low-energy limit.
The supersymmetric hypotheses requested about the spectrum of particles are:
- gauge bosons to have spin $\frac{1}{2}$ fermion partners;
- the ordinary spin $\frac{1}{2}$ quarks and leptons to have scalar partners; and
- the Higgs scalars to have spin $\frac{1}{2}$ fermionic partners.

W.J. Marciano, A. Sirlin, in Proceedings of the Second Workshop on Grand Unification, Ann Arbor, 1981, edited by J. Leveille, L. Sulak, and D. Unger (Birkhauser, Boston, 1981);
A. Sirlin, W. Marciano, Radiative corrections to $+N$ß$+X$ and their effect on the determination of 2 and sin^2_W, Nucl. Phys. B189,442 (1981);
C. H. Llewellyn Smith, J. F. Wheater, Electroweak Radiative Corrections, Phys. Lett. 105B, 486 (1981).

The following *assumptions* can be done to simplify the analysis:

- varying $\tilde{\mu}$;
- all the added supersymmetric partners have a mass $\tilde{\mu} \leq \tilde{m}_W$.

For $\tilde{\mu} \leq \tilde{m}_W$, **the β function can be investigated**.
2-loops β function is used to let the coupling from $\tilde{\mu}$ to $\tilde{m}_s$ to evolve.

Theories involving $SU(2)_L \times U(1)$
involve two parameters, the mixing parameter $\sin^2(\hat{\theta}_W$ and the parameter ρ (obtained from ν_μ deep inelastic scattering).
Such Theories predict the decay of protons. It can be avoided by:
- improving and better determining the mixing parameter $\sin^2(\hat{\theta}_W$; and
- find the pertinent agreement of ρ.

Satisfactory Weinberg angle

It is possible to use a satisfactory Weinberg angle instead of using the VEV's techniques at $\sim 10^9\,GeV$:
- from irrep.'s for fixing the charge shifts of the two conjugated families.

L.F. Li, F. Wilczek, Price of Fractionally Charged Particles in a Unified Model, Phys. Lett 107B, 64 (1981).

Remarks on $SU(7)$ *fractons*

Differently, the choice of $SU(7)$ allows one to avoid $\alpha m_{ss} \lesssim m_W$, i.e. the mixing Weinberg parameter (too high in minimal $SU(5)$ supersymmetric GUT's).

The choice of $SU(7)$ with fractons allows one to avoid
$\alpha m_{ss} \lesssim m_W$,
i.e. it allows one to avoid a value of $\sin^2(\theta(m_W))$ too high in minimal $SU(5)$ supersymmetric GUT('s)
In particular, in a minimal $SU(7)$ supersymmetric GUT, which includes fractons, with the minimum two light Higgs doublets and no intermediate mass scales (not gauge-breaking mass scales and not supersymmetry-breaking mass ones) can give a value for the mixing parameter close to the experimental one.

Two charges-shifted singlets

small By assuming the two charges-shifted singlets as light, the low-energy thresholds from the charges-shifted families and their scalar partners, the errors in the one-loop calculations for the values of m_W and $\sin^2\theta$ are large enough allow for a consistent complete agreement with the experimental standard deviations.

J. Ellis , D. V. Nanopoulos, S. Rudaz, A phenomenological comparison of conventional and supersymmetric guts, Nucl. Phys. B202, 43 (1982).

Fractionally-charged-QCD-singlet particles

An $SO(18)$ GUT can contain fractionally-charged-color-singlet fermions and exotic quarks.
The interest in this model is i that it can be broken up to $SU(3)_c \times U(1)_{em}$.

Given T the generators of the $SO(18)$ subgroups, three different ways to define the electric-charge operator Q are possible.
The differences in the ways of the assignments of the charge operator are due to the presence of 'auxiliary' symmetries within the steps of the breach.

The generalized charge operator Q' is defined as
$Q' = Q + \sqrt{2}aT_3^{L'} + \sqrt{2}bT_3^{R'} + \sqrt{2}cT_3^{L''} + \sqrt{2}dT_3^{R''}$,
with a, b, c, d constants:
- $a = c = 0$, $b = 1/3$, $d = 2/3$;
- $a = c = 0$, $b = d = 1/3$;
- $a = b = c = d = 1/3$.
(- $a = b = c = d = 0$).

F. X. Dong, T. s. Tu, P. y. Xue and X. j. Zhou, $SO(18)$ grand unified models with fractionally charged color singlet particles, Annals Phys. **145** (1983), 1.

Proton stability and neutrino masses

The problem of the proton stability and that of the neutrino masses have been proposed to be discussed unficatedly by hypothesizing the existing of a further single field.

A $U(1)_{B-L}$ broken by the presence of a single field of charge 2; this way,
- the remaining $Z-2$ symmetry avoids the proton to decay;
- the charge-2 filed
  - can couple with rh ν's and lh ν's;
  - endows the lf ν's with a large mass;
  - allows fractionally-charged particles to acquire a large mass.

J.S Hagelin, Recent progress in 4D string-model building Proceedings Of The 1990 Meeting Of The Division Of Particles And Fields Of The Aps, Bonner Billy E, Miettinen Hannu E Ed.'s, World Scientific Co. Pte. Ltd, Loi Printing Pte. Ltd, Singapore, (1990), p 827.

The model $SO(10)$ gauge symmetry

The model $SO(10)$ gauge symmetry is considered for the breach at the string level to
- $SO(6) \times SO(4) \times SU(5) \times U(1)$, and
- $SU(3) \times SU(2) \times U(1)^2$.

The investigation is conducted about the *thermal history* of the Universe. The resulting exotic-matter states can be stable, and are demonstrated to be classified according to the properties of the $SO(10)$ symmetry breaking.

S. Chang, C. Coriano and A. E. Faraggi, Stable superstring relics, Nucl. Phys. B **477** (1996), 65-104 [arXiv:hep-ph/9605325 [hep-ph]].

For $SO(10)$, the states have non-standard charges under the $U(1)_{Z'}$ symmetry, as embedded in SO(10), and are orthogonal to $U(1)_Y$:
- these states are stable if the $U(1)_{Z'}$ gauge symmetry
  -is unbroken down to low energies, or;
  - if some residual local discrete symmetry is still unbroken after the $U(1)_{Z'}$ symmetry breaking.

Fractional-charge particle stable under the $U(1)_{Z'}$ symmetry

1) The densities of fractionally-charged hadronic bound states at low temperature are severely constrained and cannot avoid decaying without the hypothesis of an inflationary phase of the Universe. The constraints are aimed at allowing the model with current Astrophysical evidences.

2) Differently, under a non-Abelian gauge group the fractionally-charged states are confined,
s.t. they would form integrally-charged bound states:
this way, the conditions established should not be violated.

3) At lowering temperatures connected with the expansion of the universe, the remaining fractionally-charged hadrons are predicted to give rise to bound states of integer charge with fractionally-charged heavy leptons.

4) The static properties of hadrons, i.e. electromagnetic mass splitting of mesons containing heavy-light quarks are model-dependent;
transition and elastic form factors are calculated in the heavy-quark effective theory:
this way, it is possible to calculate the mass-splitting relation between the two heavy-light mesons $\tilde{U}_0$ and $\tilde{U}_1$.

A. Gould, B. Draine, R. Romani, S. Nussinov, Neuton stars: Graveyard of charged dark matter, Phys. Lett. B238 (1990) 337.

Consequences of conservation of baryon parity

Within the framework of the **thermal history of the Universe**, high-energy quark from the decay from a heavy particle (i.e. inflatons, modulus or gravitino) can be demonstrated to undergo flavor oscillation and is thermalize after scatterings with the ambient thermal plasma, the scattering being due to the presence of a dimension-nine-baryon-number-violating operator because of the presence of e baryon number symmetry operator, which conserves the baryon parity.

T. Asaka, H. Ishida and W. Yin, Direct baryogenesis in the broken phase, [arXiv:1912.08797 [hep-ph]].

Evolution of barionic matter and of fractionally-charged particles

The evolution of barionic matter and of fractionally-charged particles within the thermal history of the Universe, as well as a description of the pertinent experimental probes and investigation, has been established.

L. Perl, Peter C. Kim, Valerie Halyo, Eric R. Lee, Irwin T. Lee, The Search for Stable, Massive, Elementary Particles, Int. Journ. Mod. Phys. A 16, pp. 2137 (2001).

Further models involving Mirror Symmetry

- experimental verifications of the parameter space of supersymmetric GUT theories including also a Yukawa coupling;
W. de Boer, R. Ehret and D. Kazakov, Predictions of SUSY masses in the minimal supersymmetric grand unified theory, Z. Phys. C **67** (1995), 647-664.

- fractionally-charged branes on orbifold are predicted by including also mirror symmetry.
D. E. Diaconescu, J. Gomis, Fractional branes and boundary states in orbifold theories, JHEP **10** (2000), 001.

- anyon quasiparticles with fractional quantum numbers are investigated on orbifolds.

M. Atiyah, M. Marcolli, Anyons in geometric models of matter, J. High Energ. Phys. 2017, 76 (2017).

- within the framework of mirror symmetry in $N = 2$ superconformal field theories, charged particles acquire fractional exchange statistics parametrized by the phases;

- the model exhibits charge non-conservation for the $U(1)$ particles, which applies to **quantum Hall effect**.

L. Cooper, I. I. Kogan, R. J. Szabo, Mirror maps in Chern-Simons gauge theory," Annals Phys. **268** (1998), 61-104 [arXiv:hep-th/9710179 [hep-th]].

Higher-dimensional-structures relic fractionally-charged particles

- the $SO(10)$ gauge symmetry has been demonstrated to break at the string level.

-"Wilsonian particle", '*uniton*': heavy down-like quark (standard down-like charge assignment):
  - fractional charge under the $U(1)_{Z'}$ symmetry:
    $\Rightarrow$ the uniton may be stable.

S. Chang, C. Coriano, A. E. Faraggi, Stable superstring relics, Nucl. Phys. B **477** (1996), 65-104.

Symmetry broken as

- $SO(10) \rightarrow SU(3) \times SU(2) \times U(1)^2$;

$\Rightarrow$ exotic matter states

  - classified according to the patterns of the $SO(10)$ symmetry breaking;

- in $SU(3) \times SU(2) \times U(1)^2$ type models,

  one also obtains states with:

  - regular charges under the Standard Model gauge group, but
  - with fractional charges under the $U(1)_{Z'}$ symmetry;

- fractionally charged $SU(3)_C \times SU(2)_L$ singlets:

in $SO_(6) \times SO_(4)$ these states are doublets of $SU(2)_R$ with zero $U(1)_C$ charge and an $SU(3)_C$ singlet in the quartets of $SU(4)$ with zero $U(1)_L$ charge:

in standard-like models these states are $SU(3)_C \times SU(2)_L$ singlets with electric charge $Q_{em} = \pm 1/2$, i.e.:

- $SO(10) \to SO(6) \times SO(4)$:
  - fractionally-charged standard-like-model states,
    - $SU(3)_C \times SU(2)_L$ singlets with $Q_{em} = \pm\frac{1}{2}$,and
    - (fractional) charge under $U(1)_Y$:

$[(1,0);(1,\pm1)]_{(\pm1/2,\mp1/2,\pm1/2)}$where the pedices denote the $U(1)_Y$ charge,

$[(1,\pm3/2);(1,0)]_{(\pm1/2,\pm1/2,\pm1/2)}$;

- $SO(10) \rightarrow SU(5) \times U(1)$:
  - exotic states,
  - $SU(3)_C \times SU(2)_L$ singlets with $Q_{em} = \pm\frac{1}{2}$
    $[(1, \pm 3/4); (1, \pm 1/2)]_{(\pm 1/2, \pm 1/4, \pm 1/2)}$;

-$SO(10) \rightarrow SU(3) \times SU(2) \times U(1)^2$:

- **standard-model singlets with nontrivial** $U(1)_{Z'}$;

- **heavy particles**:
  - **(low energy limit)** $SU(2)_L$ **doublets and singlets**, which are
  - $SU(3)$ singlets
    $(1, 2)_0, (1, 1)_{1/2}$,
  - lepton-like,
  - fractional electric charge $Q_{em} = \pm 1/2$;

- **fractionally charged vector- like quarks**:

$(3, 1)_{1/6}$ (*sexton*, color triplet),

- which can interact with u and d quarks and **origin stable baryons and stable mesons**;

- with fractional electric charge of $\pm 1/2$ and $\pm 3/2$

- lower bound for the masses:

- $M \sim \frac{eV}{{Y_0}^{FC}} > 10^{-19} GeV$

Particle Data Group, Review of Particle Properties, Phys. Rev. D50 (1994) 1173.

- ${Y_0}^{FC}$ **relic density of fractionally-charged matter**,

$${Y_0}^{FC} < 10^{-19} {Y_0}^{B} < 10^{-19} \frac{eV}{m_p} \sim 10^{-28};$$

- **experimental searches for free quarks in various materials**:
  - *upper bound on the number density of fractionally-charged-particles smaller than* $10^{-19} \sim 10^{-26}$;
  - *experimental constraints: densities of fractionally charged bound states have suppressed densities.*

exotic stable quarks $Q = -1/3$ forbidden:
strict constraints from cosmology

- constraints from *superheavy-elements searches*;
- request that heavy particles, after *capture by neutron stars*, do not induce the collapse of the object into a black hole:
- $\Rightarrow$ look for a mechanism that allows for the **decay of the** $Q = -1/3$ **quarks**.

E. Nardi, E. Roulet, Are exotic stable quarks cosmologically allowed?, Phys. Lett. B245 (1990) 105.

- Sexton σ: Charge $= 1/6$, and
- fractionally charged leptons,

  - *confinement temperature*, the sexton σ can form:
    - neutral color singlet bound states,
    - charged color singlet bound states,
      $\sigma\sigma\sigma$, $\sigma\sigma q$, $qq\sigma$, $\bar{q}\sigma$, and
    - the corresponding antiparticles
      $\bar{\sigma}\bar{\sigma}\bar{\sigma}$, $\bar{\sigma}\bar{\sigma}\bar{q}$, $\bar{q}\bar{q}\bar{\sigma}$, $q\bar{\sigma}$,
      - with q ordinary quarks.

- **integer-charged final states can reconvert into fractionally charged states**,
  - due to the presence of a large amount of ordinary particles;
- cooling temperature (expansion of the universe):
  - possibility for the remaining fractional hadrons to form:
    - bound states of integer charge with fractionally-charged-heavy leptons

$(1,2)_0$ and $(1,1)_{1/2}$ with $Q_{em} = T_3 + Y$,

$\Rightarrow$

neutral heavy hydrogen-type bound states $B_{1/2} + L_{-1/2}$,
which can capture an electron at a
temperature of a few eV, whose **cross-section** is calculated to be **extremely small**.

-$SO(10)$ symmetry breaking of $SU(3) \times SU(2) \times U(1)^2$

$\Rightarrow SU(3)_c \times SU(2)L \times U(1)_Y$ singlet with non-standard $U(1)_{Z'}$ charge,

- interactions with the Standard Model states vanish to all orders of non-renormalizable terms

 if the $SU(3)_H$ is left unbroken, but

- $U(1)_{Z'}$ should be broken between the weak scale and the Planck scale:
- W-singlet W_s:
  - interaction is suppressed by $1/M^2{}_{Z'}$,
  - (can be classified as WIMP);
  - can annihilate into:
    - two light Standard Model fermions, and
    - their superpartners;
  - further conditions on the W-singlet: mass (wrt $M_{Z'}$) and inflation;
  - can be a strongly interacting particle.

Further analysis of the SO(18) model

The breaking of the SO(18) supersymmetric model has been analyzed to be possible through **several mechanisms**.
The generalized charge operator Q' for states is obtained as
$Q' = Q + \sqrt{2}aT_3^{L'} + \sqrt{2}bT_3^{R'} + \sqrt{2}cT_3^{L''} + \sqrt{2}dT_3^{R''}$,
as fractionally charged color singlet particles
- where the parameters a, b, c and d appear in the definition of the generalized electric charged operator Q' of the 256-dimensional irreducible representations.

F. X. Dong, T. S. Tu, P. y. Xue and X. j. Zhou, $SO(10)$ grand unified models with fractionally charged color singlet particles, Annals Phys. **145** (1983), 1.

- *'model 1'* :

parameters of the generalized charge operator: $a = c = 0$, $b = 1/3$, $d = 2/3$

- color singlets with charge $Q = 1/3, 2/3, 4/3, 5/3, 2$, or
- with right-handed current.

- *'model 2'*:

because of the symmetry, cannot have $SU(3)_c \times SU(2) \times U(1)$ invariant masses

parameters of the generalized charge operator: $a = c = 0$, $b = d = 1/3$;

- i.e., six generations of ordinary fermions which can not acquire (because of the symmetry breaking) $SU(3)_c \times SU(2) \times U(1)$ invariant masses, and

- ten generations of non-standard fermions, among which also fractionally-charged color-singlet particles:

$Q = 1/3, 2/3, 4/3, 5/3.$

The **color singlets can acquire masses** because, in the two models, the symmetry G' is not needed.

The color singlets predicted

- do not interact with usual quarks via the gauge bosons: **stable**;
- experimental observation has bee proposed;

L. L. Chau, ISABELLE Proceeding of the 1981 Summer Workshop, BNL 745, Vol. 2, 1981.

- under the hypotheses they have

  unstandard properties like charge, color, or weak isospin,

  provided that they are not prohibitively massive,

  experimental observation has been proposed.

A. Ali et al., ISABELLE Proceeding of the 1981 Summer Workshop, BNL 503, Vol. 2, 1981.

  - experiment cancelled.

Brookhaven National Laboratory (2004), The long road from ISABELLE to RHIC, U.S. Department of Energy;

Frederick E. Mills (1973). ISABELLE Design Study., IEEE Transactions on Nuclear Science. 20 (3): 1036-1038.

More about FCHAMP's

- FCHAMP's:
-leptons with:
  - fractional e.m. charge,
  - electroweak charge,
  - with non-trivial hypercharge $U(1)_Y$,
  - no strong interactions, and
  - of mass m and charge $Q_L \simeq 2$;

- **Early Universe**: possibility to retrieve items of information about FCHAMP's for:

- thermal production,
- annihilation,
- survival,
- cosmological constraints from primordial nucleosynthesis,
- cosmological constraints form microwave-background-radiation, and
- abundance on Earth;

P. Langacker, G. Steigman, Requiem for a fractionally charged, massive particle, Phys. Rev. D 84, 065040 (2011).

- no strong interaction theoretical investigations.

B. Acharya *et al.* [MoEDAL], The Physics Programme Of The MoEDAL Experiment At The LHC, Int. J. Mod. Phys. A **29**, 1430050 (2014).

Doubly-Charged Massive Stable Particles

The facts about **detection of stable particles with** $Q_{em} = 2$ is revised.

- *XY* gauginos and warped extra dimensional models:
  - GUT parity, and
  - effective TeV-scale supersymmetric grand unification;

- doubly-charged leptons within 'modern' walking technicolor models (Minimal Walking Technicolor):
  - (predictions of large Flavour-Changing Neutral Currents (FCNC's) and a great variety of technimesons rejected because no experimental evidence was produced);
  - walking behaviour: slow running of the technicolour gauge coupling over an extended range:

- masses expected to exceed 100 GeV,
- lightest technibaryon stable,
- electric charges of the UU, UD, and DD
  equal $n+1$, n, and $n-1$, respectively, n arbitrary real number;
- fourth family of leptons:
- new 'neutrino' ν' and a new 'electron' e',
- hypercharges $(-(3y-1)/2)$ and $-(3y+1)/2)$, resp.:

for the analysis in [**?**], the simplest choice $y=1$ has been perfomed,

for $y=1$, electric charges of the new leptons -1 and -2, resp;

- two kinds of stable doubly-charged particles:
  - technibaryon UU^{++}, and
  - technilepton e'^{++}:

- Doubly-charged Higgs bosons in $L-R$;

- (Higgs triplets containing) doubly-charged Higgs bosons $\Delta^{++}{}_R$ and $\Delta^{++}{}_L$
(amplitudes of the vector boson fusion processes proportional to v_{L-R} VEV's of the neutral members of the scalar triplets);

- $\Delta^{++}{}_L$ suppressed;

- the doubly-charged Higgs boson quasi-stable for very small Yukawa couplings;

- doubly-Charged Higgsinos in the $L - R$ supersymmetric model:
  - *with doubly charged Higgs bosons*, doubly charged Higgsinos can be long-lived enough to be detected;

- doubly-charged leptons in the framework of almost-commutative geometry:
  - no other SM gauge charges;
  - stable **because of** the absence of mixing with light fermions.

Further researches

- searching large samples for fractional charge of any compositions;
  experimental search for particles with fractional charge in free states;
  grounded Faraday cup and high-impedance amplifier.

W.R. Innes, M.L. Perl, J.C. Price, A rotor electrometer for fractional charge searches, In Proceedings of the 4th International Conference on Muon Spin Rotation, Relaxation and Resonance, Uppsala, Sweden, 23-27 Jun 1986.

- search for fractional-charge leptons and quarks in an unconfined state.

M. Perl, E. Lee and D. Loomba, A Brief review of the search for isolatable fractional charge elementary particles, Mod. Phys. Lett. A 19 (2004), 2595.

- search for 4-th-generation integrally-charged quarks.

X. He, S. Pakvasa and H. Sugawara, Are 4-th-generation quarks integrally-charged? Annals N. Y. Acad. Sci. 518, 332 (1987).

- search for fractionally-charged particles in (Anti)-neutrino - Deuterium Interactions.

D. Allasia, C. Angelini, A. Baldini, F. Bianchi, F. Bobisut et al., Search for Fractionally Charged Particles in (Anti)-neutrino - Deuterium Interactions, Phys.Rev.D 37 (1988) 219.

- search for fractionally-charged-particles with an electric charge $q = e/5$ (and opportune velocities).

MACRO Collaboration, Final search for lightly ionizing particles with the MACRO detector, [arXiv:hep-ex/0402006 [hep-ex]].

- search for isolated fractionally-electrically-charged particles with the Millikan method.

E. R. Lee, V. Halyo, I. T. Lee and M. L. Perl, Automated electric charge measurements of fluid microdrops using the Millikan method, Metrologia, 41 (2004), S147-S158.

Thank You for Your attention.