Some aspects of fractons

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30/05/2020

Abstract

Fractionally-charged-particles (fractons) have been theorized in several models. Hadronic-matter fractons might be resulting in the description of new-long-range interactions; leptonic fractons can be obtained after several kinds of supersymmetric theories.
Fractons can be looked for in Early Cosmology, Cosmology, in Galactical material, in material around celestial bodies (i.e. the Sun), in meteoritic material and on the Earth. The experimental search for fractons can be achieved in accelerator experiments, cosmic-rays experiments, mass-spectrometer experiments, cantilever experiments and experiments involving the gravitational interaction as well.
Other experimental limitations and theoretical constraints have to be taken into account.

Particles-recombinations modes and experimental searches are exposed.

Summary

- Search for new long-range forces.
- Kinds of Fractons.
- Fractons from supersymmetric theories.
- Experimental searches for fractons:
  - accelerator experiments;
  - cosmic-rays experiments;
  - mass-spectrometer experiments.
- Fractons from Gravity experiments.
- Other experiments about fractons.

- Particles-recombinations products and experimental searches.

Search for new long-range forces

The G_Y interaction - standard-model particles ($_o$-particles:

photons, gluons, intermediate vector bosons V_o, and quarks and leptons fermions F_0);
- 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.
- $_0$-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 $\rightarrow$ $_Y$-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

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

with

- $G_{W \quad \_S} = SU(2) \times U(1)$,
- $SU(3)_c$ 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 consising of light 0-quark pairs, the contrbution of X quark pairs being negligible;
- Y hadrons produced from the 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.

Fractons from Supersymmetric models

Fractionally-charged particles (leptons) have been proposed also as a probe for supersymmetric theories.
By 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.

- $\frac{1}{3}e$-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 $50 - 100GeV$ to be evaluated in $\bar{p}p$ and e^+e^- experiments.

P. Frampton and T. Kephart, Fractionally Charged Particles as Evidence for Supersymmetry, Phys. Rev. Lett. **49** (1982), 1310

Electroweak but not strong interations

The 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.
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 and 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;
- $\check{C}$erenkov-effect experiments;
- Emulsion experiments (after some symmetry-breaking mechanisms).

Comparison of accelerators experiments

Summary of accelerator searches

First author or collaboration	Ref.	Exp. type	Beam + target	Quark identification	Quark's charge[a]	Quark's mass[b]	Results	Comments
Price	[41]	Anomalons	1.8A GeV Ar on plastic detector	Etch pits in plastic detector	$n/3$		$<3\times10^{-3}$ fr.ch./int	
Barwick	[167]	Anomalons	1.8A GeV Ar on Č detector	Č signal	$n/3$		$<10^{-4}$ fr.ch./int	No anomalon effect
Bloomer	[42]	Anomalons	1.9A GeV Fe on emulsion	Lacunarity of emulsion track	$n/3$		$<3\times10^{-3}$ fr.ch./int	Secondaries of charge 1–3
Bland	[44]	Heavy ion	1.9A GeV Fe on lead	Millikan	$n/3$		$<5\times10^{-7}$ or $<5\times10^{-5}$ q/int	Somewhat model dependent
Bland	[47]	Heavy ion	2.2A GeV Si on silicon	Millikan	$n/3$		$<3\times10^{-5}$ q/int	More model dependent
UA2	[180]	Hadronic	$\bar{p}p$ at $\sqrt{s}$ of 540 GeV	Pulse height	1/3 2/3	<3 <2	$<2\times10^{-3}$ q/unit ch	
E-497	[172]	Hadronic	400 GeV/c p on copper	Mass from Č ring radius	1	See fig. 4	See fig. 4	
CHARM	[183]	Hadronic	400 GeV p on copper	dE/dx	1/3 2/3	<12 <12	$\sigma<3\times10^{-40}$ cm^2 $\sigma<2\times10^{-39}$ cm^2	White quarks
EMC	[51]	D.I.S.	200 GeV/c muons on berrylium	Pulse height	1/3 2/3	<15 <9	$<10^{-5}$–10^{-6} free q/virtual q	
WA44	[54]	D.I.S.	Wideband ν and $\bar{\nu}$ on lead	Avalanche chamber	1/3, 2/3		$<10^{-4}$ q/int	Includes q within jets Ignores absorption in target
CHARM	[183]	D.I.S.	Wideband ν and $\bar{\nu}$ on CDHS	dE/dx	1/3, 2/3	2	<1–3×10^{-5}q/int	White quarks
			Wideband ν and $\bar{\nu}$ in CHARM	dE/dx	1/3, 2/3		See table 2	Ordinary quarks
Mark II	[58, 128]		e^+e^-	p and dE/dx	1 Inc 2/3 Inc 2/3 Exc	1.7-3 1–3 1–2.8	$R<2\times10^{-3}$ $R<8\times10^{-3}$ (fig. 7(d)) $R<5\times10^{-4}$ (fig. 7(b))	SPEAR
TPC	[57]		e^+e^-	p and dE/dx	1/3 Inc 2/3 Inc 4/3 Inc	<14 <13 <9	(fig. 7(c)) (fig. 7(d)) (fig. 7(e))	PEP
JADE	[130]		e^+e^-	p and dE/dx	1/3-2 Inc	<20	(fig. 7(c)–(e))	PETRA
FQS	[59–61]		e^+e^-	TOF and dE/dx	1/3, 2/3 Inc 1/3, 2/3 Exc 1/3 Inc 1/3, 2/3 Exc	<14 <12 	(fig. 7(c), (d)) (figs. 7(a), (b)) (fig. 11) (fig. 11)	PEP Large σ quarks Large σ quarks

[a] The symbol $n/3$ refers to searches for quarks of third-integral charge. The e^+e^- experiments are labelled "Inc" or "Exc" for inclusive or exclusive searches respectively.
[b] Masses are given in GeV.

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

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

T. Mashimo et al., Phys. Lett. 128 (1983) 327; Lett. Nuov. Cim. 41(1984) 315;
S.P. Ahien and K. Kinoshita, Phys. Rev. D 26 (1982) 2437;

D.M. Ritson, Magnetic monopole energy loss, SLAC-Pub 2950 (1982).

- 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

Cosmic ray results

First author or collab.	ref.	Quark identifn.	Quark's charge + mass	β	Result[a]	Comment
FQS	[63]	dE/dx + TOF	1/3, 2/3 1, 4.2 GeV	>0.1 0.4–0.7	$\phi < 3 \times 10^{-9}$ See fig. 12	Uses FQS apparatus for PEP
Mashimo	[65]	dE/dx + TOF	2/3 1/3, 2/3	~1 6×10^{-4}–0.4	$\phi < 2 \times 10^{-12}$ $\phi < 6 \times 10^{-13}$	Magnetic monopole search ϕ includes upward particles
Sakuyama	[90, 91]	Delayed air showers	? ~50 GeV and ~10 TeV	Just below 1	2 particles claimed to exist	
Inoue	[93]	Delayed air showers	?	Just below 1	Could be due to N and $\bar{N}$	
Bhat	[94]	Delayed air showers	?	Just below 1	$\phi < 2 \times 10^{-11}$	No events with consistent times
Mincer	[95]	Monte Carlo on delayed air showers			Previous results *not* evidence for heavies	Fluctuations on estimated energies can be large
Yock	[98]	dE/dx + TOF	Integral, ≥4 GeV	<0.65	$\phi \sim 10^{-8}$	Previous evidence for fractional charges now discounted.
Wada	[184]	dE/dx	4/3 1/3, 2/3		$\phi = 4 \times 10^{-9}$ $\phi < 9 \times 10^{-10}$	Zenith angles 31–49°
McCusker	[70]	Various (see section 3.3)	Fractional?		$\phi \sim 10^{-11}$	Claims evidence for quark globs close to shower cores

[a] The flux ϕ is quoted in particles $cm^{-2} s^{-1} sr^{-1}$.

from: 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 and G. Morpurgo, Phys. Lett. 137B (1984) 439.

- search for fracton on Earth matter:

for ractons, the reuslting 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

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

It is possible to explore the possibility for 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;

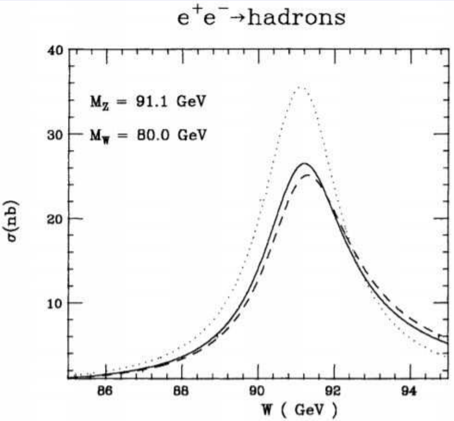

Fig. 11.12. Total hadronic cross section around Z^0 pole calculated by using the analytic result of convolution integral with radiator. The dotted line represents the Born cross section. The solid curve shows the corrected one up to $O(\alpha^2)$. That including only the $O(\alpha)$ correction, is drawn by dashed curve. No other correction from one-loop is not considered to see the effect of QED higher orders.

from: 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.

Search for fractons in baryonic matter

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

- fluctuations;
- event characterization.

P. Senger, Status of the Compressed Baryonic Matter experiment at FAIR, Int. J. Mod. Phys. E **29** (2020), 2030001 [arXiv:2004.11762 [physics.ins-det]].

High-energy hadronic processes and quarks quantum numbers

resonance production in proton-proton collisions at $\sqrt{s} = 7TeV$ and $\sqrt{s} = 13TeV$
(pp collisions and pPb 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]].

Thank You for Your attention.

Further References

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; 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;
V. Mathai, G. Wilkin, Fractional quantum numbers via complex orbifolds, arXiv:1811.11748;
I. Antoniadis, S. Dimopoulos and G. Dvali, Millimeter range forces in superstring theories with weak scale compactification, Nucl. Phys. B **516** (1998), 70-82.

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;
X. He, S. Pakvasa and H. Sugawara, Are 4-th-generation quarks integrally-charged? Annals N. Y. Acad. Sci. 518, 332 (1987);
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;
MACRO Collaboration, Final search for lightly ionizing particles with the MACRO detector, [arXiv:hep-ex/0402006 [hep-ex]];

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.