Standard Model

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Issues concerning the Standard Model of particle physics:

Even though we call it a model it is actually the candidate for **the** 'theory' of the fundamental particles and interactions among them!

Built, brick by brick, over the last 50-60 years, combining information from a lot of different types of experiments and many many innovative theoretical ideas.

The basic mathematical framework is that of quantum field theories (QFT) which possess some special properties (symmetries). Some aspects of these will be covered in lectures by Prof. Deredinger.

Using this information I intend then to cover the following :

• How did we find out about the fundamental constituents and interactions among them.

• How did we arrive at an understanding of the symmetries and hence a gauge theory description of the same: how was the SM built?

• What is the significance of the different families of quarks and leptons: flavour physics.

• What is the piece of the SM still left to be checked and how does the theory guide us about how and where to look for the missing piece.

Among the Nobels awarded for physics till to date, 15 are for Standard Model:

1. 1936: Victor Franz Hess for his discovery of cosmic radiation

   Carl David Anderson for his discovery of the positron.

2. 1950: Cecil Powell for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method. (π meson and μ)

3. 1957: Chen Ning Yang, Tsung-Dao Lee

   For their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles.

4. 1965: Sin-Itiro Tomonaga, Julian S. Schwinger, Richard P. Feynman.

   For their fundamental work in quantum electrodynamics, with profound consequences for the physics of elementary particles

5. 1969: Murray Gell-Mann

   For his contributions and discoveries concerning the classification of elementary particles and their interactions. (Quark Model)

6. 1976: Burton Richter, Samuel Ting.

   For their pioneering work in the discovery of a heavy elementary particle of a new kind. (Charmonium: bound state of charm c and anti-charm $\bar{c}$) (November revolution).

7. 1979: Sheldon L. Glashow, Abdus Salam, Steven Weinberg.

   For their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including the prediction of the weak neutral current.

8. 1980: James W. Cronin, Val Logsdon Fitch.

   For the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons. (CP symmetry)

9. 1984: Carlo Rubbia, Simon Van Der Meer.

   For their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction.

10. 1988: Leon M. Lederman, Melvin Schwartz, Jack Steinberger.

    For the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon-neutrino.

11. 1995: Martin L. Perl, Frederick Reines.

    1)For pioneering experimental contributions to lepton physics, specifically for the discovery of the tau lepton. 2) For pioneering experimental contributions to lepton physics, specifically for the detection of the neutrino.

12. 1999: Gerardus ’t Hooft, Martinus J.G. Veltman.

    For elucidating the quantum structure of Electroweak interactions in physics. (QFT description of EW interactions)

13. 2002: Raymond Davis, Jr., Masatoshi Koshiba, Riccardo Giacconi.

    1)For pioneering contributions to astrophysics, in particular for the detection of cosmic (extra terrestrial) neutrinos.

    2)For pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources.

14. 2004: David J. Gross, H. David Politzer, Frank Wilczek

    For the discovery of asymptotic freedom in the theory of the strong interaction. (QCD)

15. 2008 Yoichiro Nambu; Makato Kobayashi and Toshihide Masakawa

1)For the discovery of the mechanism of spontaneous broken symmetry in subatomic physics (Electroweak Symmetry breaking)

2) For the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature (CP violation)

SM - I

Heart of the Matter : How to determine what lies within

- Today I will mostly talk ONLY about quarks (u, d, s) and only a little about e^-, ν.

- What do we mean by Standard Model : in simple words first.

- Outline complementary ways in which we have discovered that matter has constituents.

- One way (scattering experiments) in fact uses the knowledge about how these constituents interact.

The relationship between our increasing knowledge of how constituents are put together at a given level and finding structures at a shorter distance scale is very interesting.

We theorists have been able to predict new particles sometimes inclusive of their masses (and/or new interactions), based on the knowledge available on the interactions which hold the constituents together! Experiments have confirmed or disproved this. Some of the constituents came unannounced to the party of course!

In turn the experimental results have propelled developments of new theoretical ideas.

Mainly two different ways in which we have inferred about what lies at the heart of matter.

- Use the systematics observed in the properties of the system such as mass, spin, life times.... etc.

- Scattering : Use scattering of a probe off a macroscopic body to get information about its structure.

To be more specific:

1)e^- : Discovered a bit accidentally but matched with what was expected on grounds of observed patterns and systematics: 1897-1899.

2)e^+: Predicted. Must exist if quantum mechanics of an e^- is to be consistent with special theory of relativity (1930-1933).

3)μ^- : Just came along unlooked for, unexpected, but then its study furthered our understanding of fundamental interactions.

4)$\pi^\pm$: predicted by Yukawa (1935), ν : postulated by Pauli (1931): Both found in experiments 1947.

5)Nucleus: 'discovered' by Rutherford in scattering (1911).

6)Quarks: u, d, s: postulated (1961) from study of static properties, found again in scattering experiments (1966).

What is the World around us made up of?

An AGE OLD QUERY:

- What is the HEART OF MATTER?
- How do things around us work? What are they all made of?
- Is everything made up of the *same* ultimate units? If so, what holds them together?

What are the bricks and mortar of edifice of life?

- The question has remained the same through the ages.
- Answers have changed. Our perception of what the parts are has changed as our understanding of how the parts are put together has grown!

Efforts to answer this question ⇒ the development of Science.

'ELEMENTS' : ~ B.C.

Definition of **elements** a-la the Greeks (Empedocles):

Earth

Fire

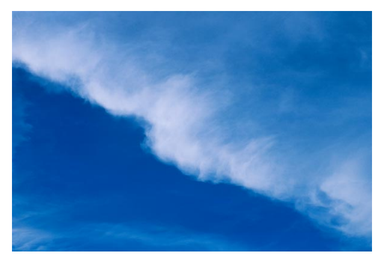
Wind

Water

The Indian Sages: Panchmahabhootas

Add the 'Aakash' (space) to the list above.

All the elemental forces of nature



Aakash

'Elements' $\rightarrow$ Chemical elements $\rightarrow$ molecules $\rightarrow$ atoms $\rightarrow$ nuclei $\rightarrow$ quarks, leptons,..

$\Downarrow$

Elementary Particle Physics

The accepted world view:

Fundamental Particles are the quarks, the leptons and gauge bosons which carry the forces: the photon, the W/Z-boson, the gluon

and

the as yet undiscovered Higgs Boson.

In principle laws of physics which govern the behaviour of these elemental blocks, allows us to predict behaviour of *all matter*.

Laws of particle physics which we have found to be functioning at distance scales of fermis and smaller, seem to be of relevance in addressing things that happen on cosmological time (say beginning of the universe) and astronomical distance scales (millions of mega parsecs and above!)

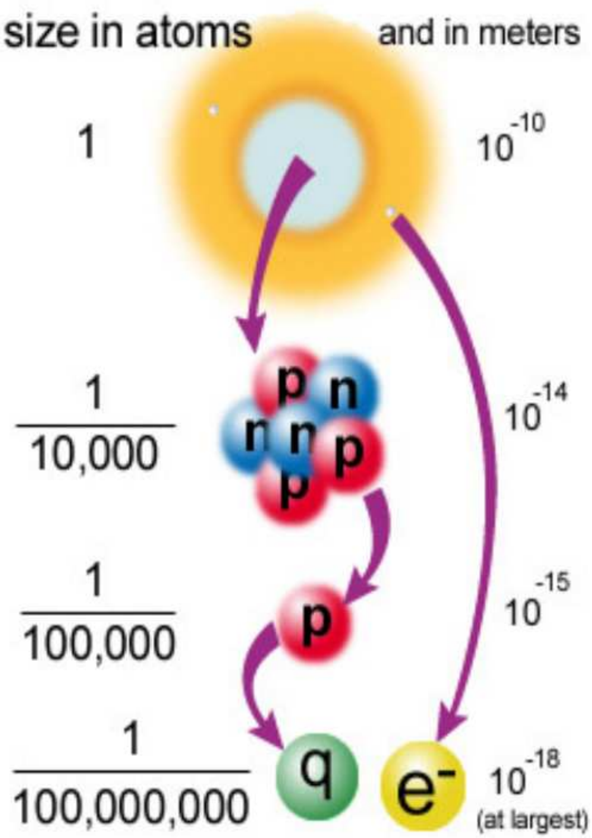
What does this subject deal with?

1. What are the elementary constituents of matter?

2. What holds them together?

3. What is the correct mathematical framework to describe how the constituents are put together to form matter, how do they interact with each other and how can one predict its behavior under different conditions?

The answers to these three questions at present are provided by the Standard Model.



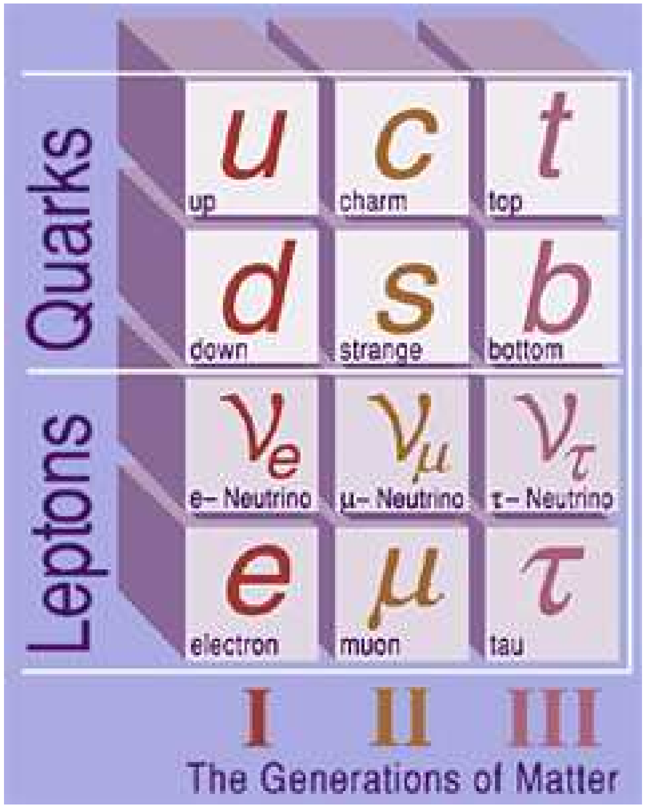
The constituents of matter at different distance scales:

Atoms: $\sim$ Angstrom $= 10^{-10}$ m;

quarks and *leptons* which are a hundred million times smaller than an atom and are today believed to be indivisible/point like.

Reminder: Experiments at high energy accelerators, and the development of theoretical models, have together helped us arrive at this

Sizes of different objects thought to be fundamental at different distance scales



BOSONS force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ (W bosons)	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

The 'Periodic Table' of Fundamental particles and their interactions has arrived!

STANDARD MODEL (SM) OF PARTICLE PHYSICS!

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Second part of 19th Century:

Faraday: electricity comes in multiples of a basic unit.

$$\Downarrow$$

Experiments with Cathode Rays by Thompson showed existence of a particle with e/m ratio different from the hydrogen ion.

The first elementary particle electron was discovered.

1897: The world of particles was born.

Thompson :

Cathode rays are matter in a new state, a state in which the subdivision of matter is carried much further than in the normal gaseous state, a state in which **all** *matter, - that is matter derived from different sources such as Oxygen, Hydrogen etc. - is one and the same kind, the matter being the substance from which all chemical elements are built up.*

Thompson thus 'split' the atom!

Three basic processes in the transition from electron being a "mathematical entity" to a "physical reality" :1897.. $>$ 1899**.**

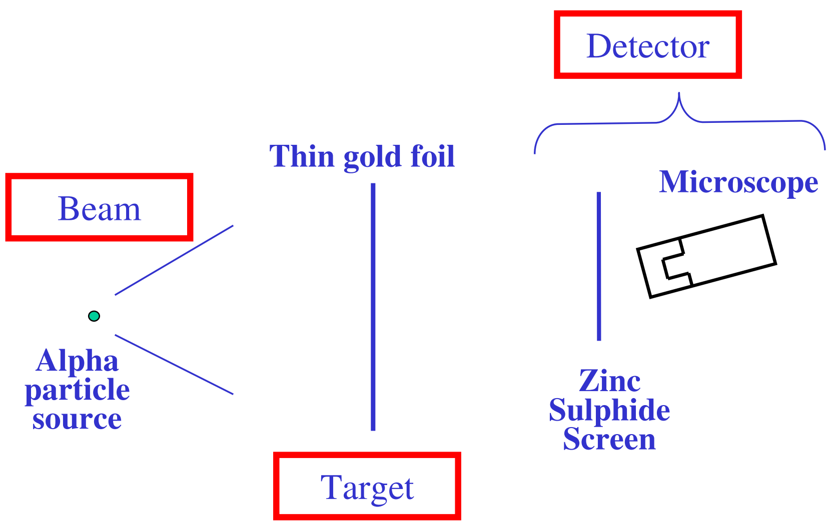
1) Observation by Faraday that the electricity comes in units from patterns in ionisation,

2) The experiments made by Thompson that Cathode rays behave under the action of electric and magnetic fields as though they consisted of particles with a ratio of charge to mass (the famous e/m) quite different from the Hydrogen ion,

3) The measurement by Zeeman of the splitting of the atomic spectral lines in a magnetic field and finding a value in agreement with that predicted using ideas by Lorenz, if an electron with that value of e/m should exist inside an atom.

Thompson: Plum pudding model of Atom with electrons sticking out like plums.

The Rutherford scattering experiment: shaped the physics of the Century!



of α particles scattered from the gold foil at different angles were counted.

Most α particles went undeflected.

BUT SOME REBOUNDED

Completely opposite to that expected if 'plum pudding model' was true.

Rutherford concluded from this: atom has a point like nucleus.

Rutherford truly split the atom into nucleus and electrons!

Why does this mean that positive charge of the atom is a 'point': the nucleus?

Rutherford:

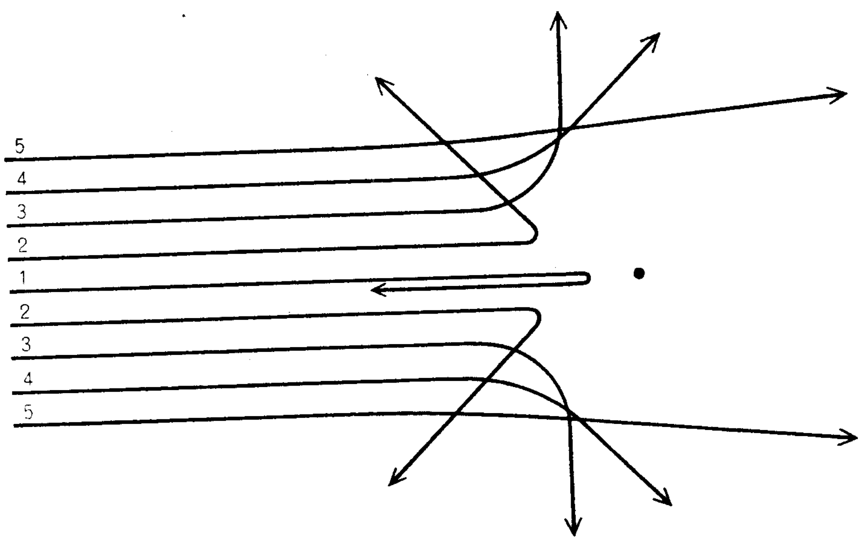
It was about as credible as if you had fired a fifteen inch shell at a piece of tissue paper and it came back and hit you

$$\Downarrow$$

Most of the atom is empty space. The $+$ve charge of atom *and* the mass concentrated in a 'point': nucleus of atoms.

[example of person crossing the road]

The α particles can 'look' inside the atom to see the 'size' of the region containing the positive charge.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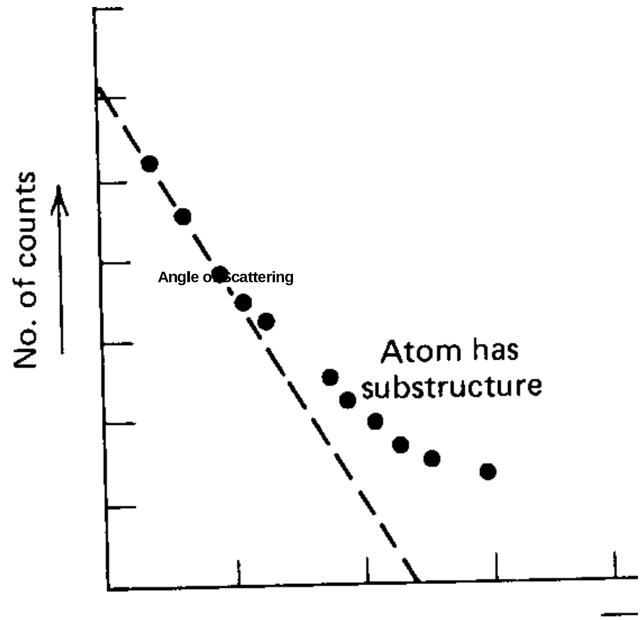

No. of counts
Angle of scattering
Atom has substructure

x-axis: angle.

Everything made up of molecules which are made up of atoms which contain 'electrons' in a lot of empty space and positively charged point 'nuclei'.

Decade of Atomic Physics and Nuclear Physics!

Discovery of Radioactivity played a big role in this period and these discoveries.

Nuclei seemed to transform spontaneously into each other!

The 'mass' of the nuclei was in approximate integral multiples of Hydrogen nucleus.

Patterns in nuclear masses, their spin angular momenta $\Rightarrow$ nuclei too are made up of smaller units : proton and the neutron.

If the 'size' seems to be smaller than the least count of our best measuring stick does not mean that the object may not have constituents.

Fundamental objects at this point: the photon γ, electron e, the proton(p) and the neutron (n).

one more got added a'la Pauli (1930-1931)!

THE NEUTRINO.

In β decays:

Nucleus (Z p, Nn) $\rightarrow$ Nucleus' (Z $\mp \mathbf{1}p$, N $\pm \mathbf{1}n$).

Thus effectively a proton converts into a neutron or vice versa and a positron or electron is emitted.

Free neutron was discovered by Chadwick in 1936!

Found to decay $n \rightarrow p + e^-$

The electron energy seemed to vary continuously in β decays as well as the n decay: at variance with conservation of energy, also of linear and angular momentum!!

'Small neutron': neutrino postulated by Pauli to preserve conservation of energy, angular momentum in nuclear β decay.

All the conservation laws are related to some symmetry or the other!

Example: Conservation of linear momentum: laws of physics do not depend on the position where the experiment is performed.

An example of an invariance predicting a particle!

To repeat again and again!

Note that the nucleon structure of a nucleus was arrived at by observation of patterns in properties of nuclei.

The nucleons *neutrons and protons* were observed outside the nucleus.

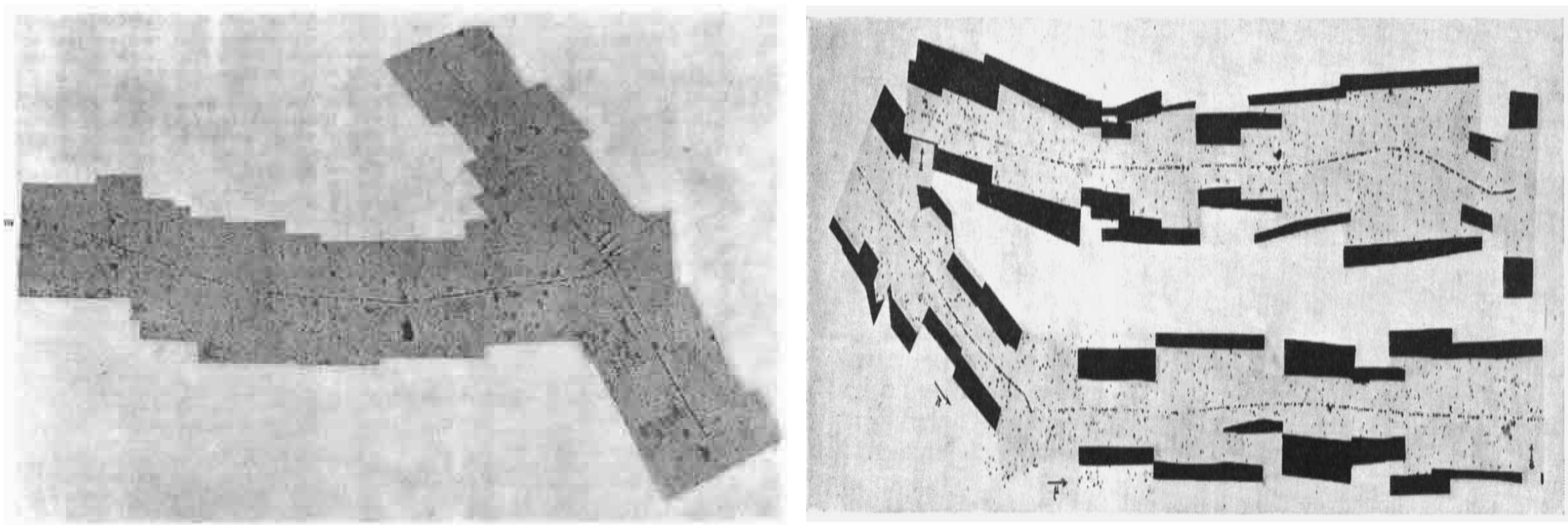
Needed more energetic particles to unravel the secrets. Nuclear reactions.

Rutherford: It has long been my ambition to have available a copious supply of atoms and electrons which have energies transcending those of the α , β particles from the radioactive bodies.

1)Man made accelerators:

2)'Natural' Accelerators: Cosmic Rays

1947: Powell and collaborators found π, μ in cosmic rays!



G.P.S. Occihialini and C.F. Powell (Nature 159, 186, 1947), Lattes, Ochhihialini, Powell (Nature 160, 453, 1947)

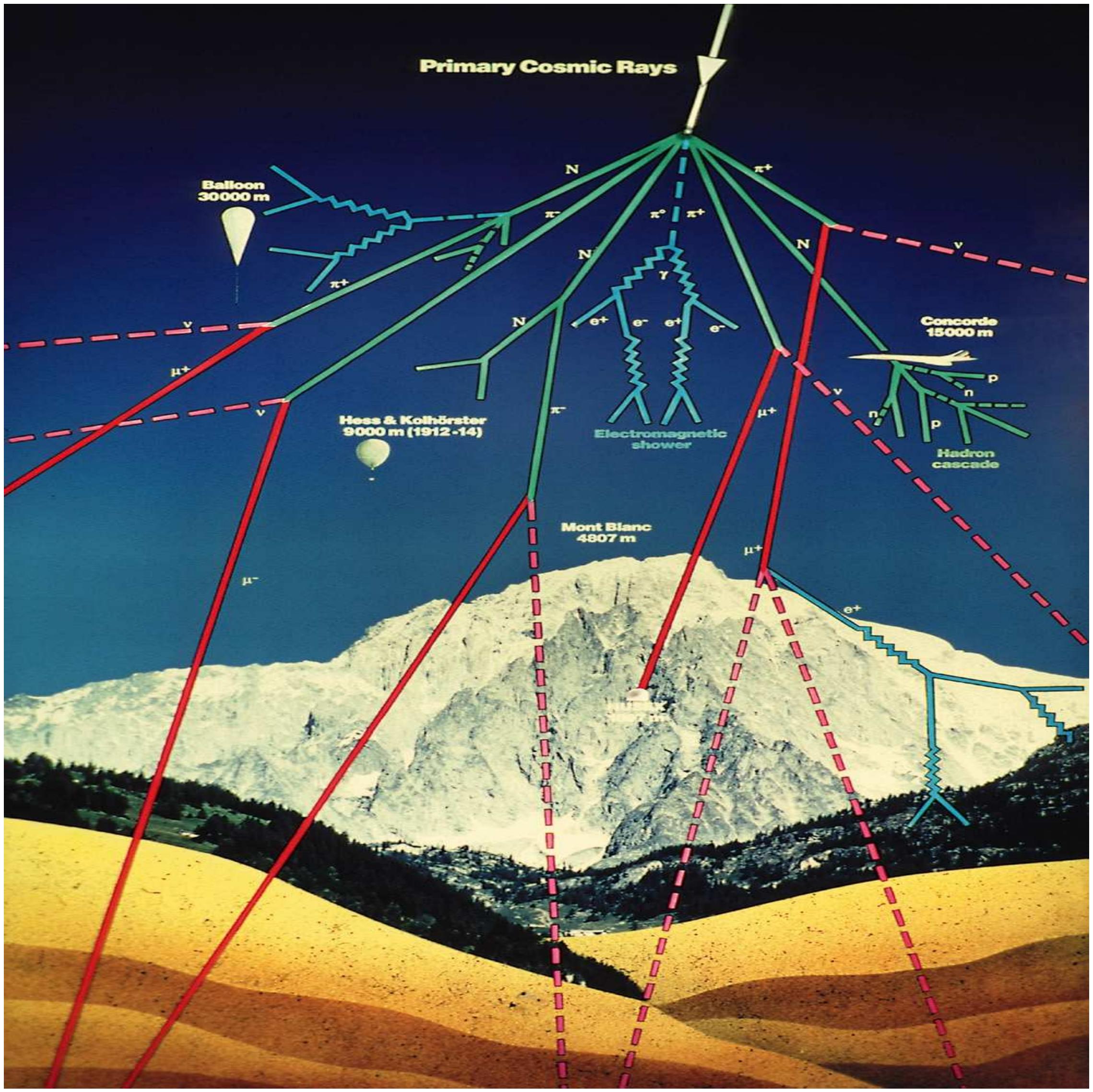
π, μ similar masses BUT different properties!

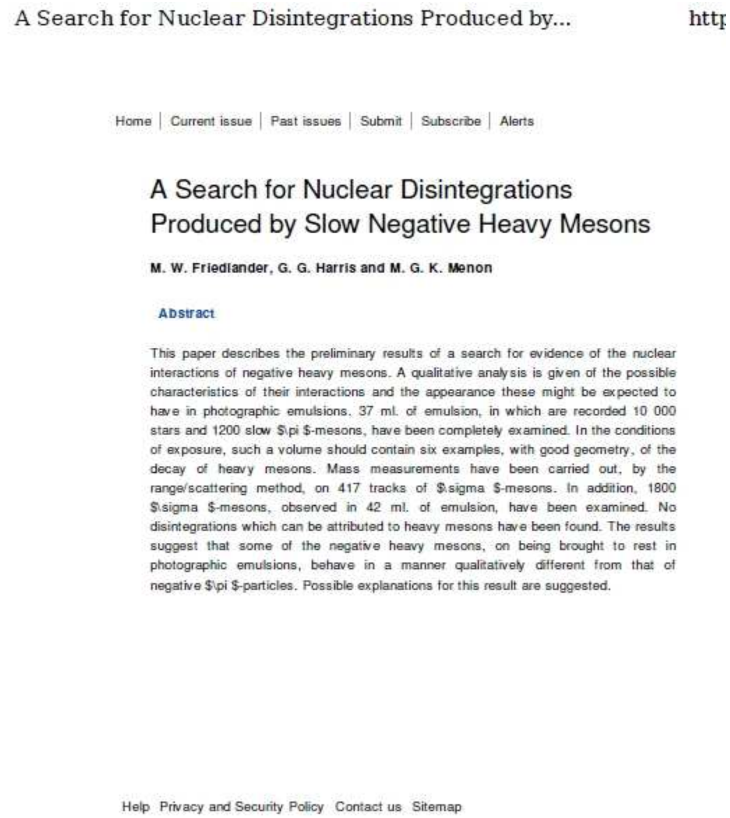
π : suggested by Yukawa in 1935 (more about it tomorrow), found in 1947!

μ : unexpected.

True for leptons! by and large they came to the party unlooked for! (later)

1897 to 1947: Half a century of particle physics. γ, e^-, e^+, p, n, ν, π, μ .





A Search for Nuclear Disintegrations Produced by... http

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A Search for Nuclear Disintegrations Produced by Slow Negative Heavy Mesons

M. W. Friedlander, G. G. Harris and M. G. K. Menon

Abstract

This paper describes the preliminary results of a search for evidence of the nuclear interactions of negative heavy mesons. A qualitative analysis is given of the possible characteristics of their interactions and the appearance these might be expected to have in photographic emulsions. 37 ml. of emulsion, in which are recorded 10 000 stars and 1200 slow $\pi $-mesons, have been completely examined. In the conditions of exposure, such a volume should contain six examples, with good geometry, of the decay of heavy mesons. Mass measurements have been carried out, by the range/scattering method, on 417 tracks of $\sigma $-mesons. In addition, 1800 $\sigma $-mesons, observed in 42 ml. of emulsion, have been examined. No disintegrations which can be attributed to heavy mesons have been found. The results suggest that some of the negative heavy mesons, on being brought to rest in photographic emulsions, behave in a manner qualitatively different from that of negative $\pi $-particles. Possible explanations for this result are suggested.

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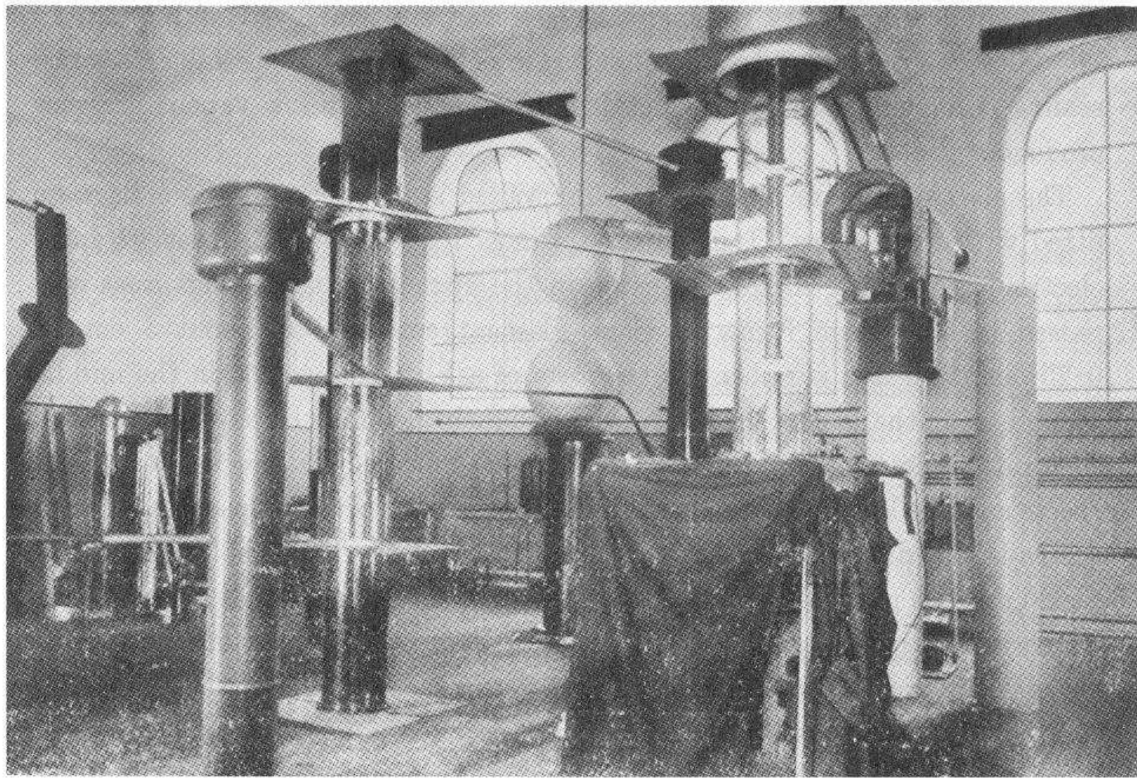
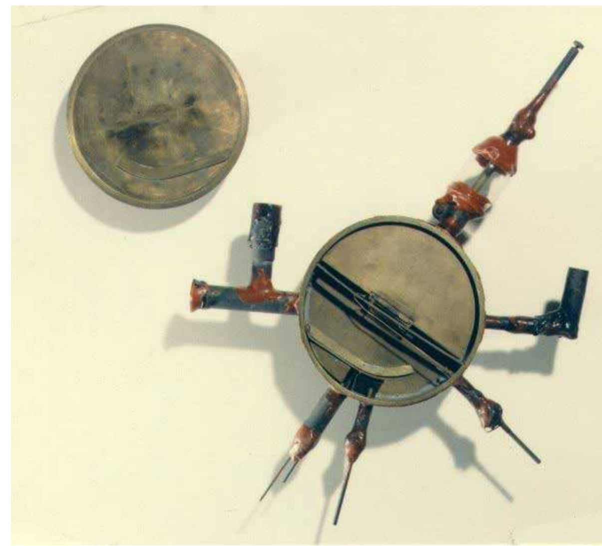
Reference: Proc. R. Soc. Lond. A January 1954, vol. 221 no. 1146 394-405.





Cockroft-Walton Accelerator

Fitted inside a room (1931)

First Cyclotron(4.5 inches)

Lawrence-Livingston (1933)

11 inch: accn. to 1 MeV.

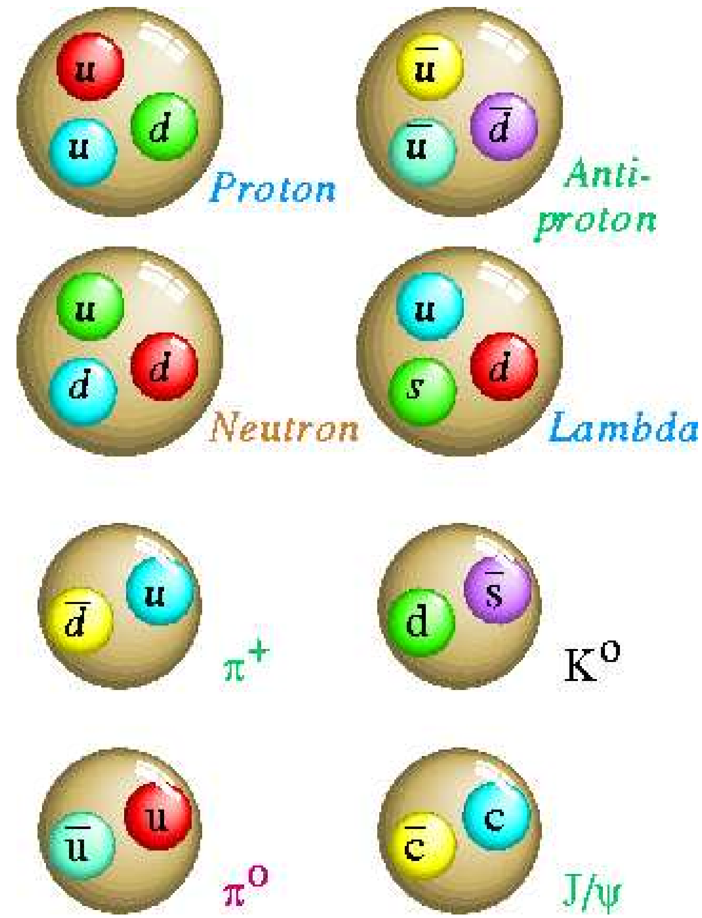
(from aip/history web site)

1947 onwards: Large number of newer particles just like the proton, neutron and pions.

Some so called 'strange' particles: because they were produced at the same rates like protons, pions but lived much longer! Determination of their masses, life times, interactions! (a bit about it tomorrow)

All of them can not be **fundamental**.

Gell-Mann-Zweig Quarks: circa 1960
All these observed patterns in the properties of these 'heavy' particles **Hadrons** (Baryons and Mesons) are explained by assuming that they are made of even more fundamental objects **Quarks**. Quark Model



Only three types required : u, d, s

Story of c and heavier quarks will be taken up later.

Observation by Gell-Mann and Zweig: Pattern and the regularity exhibited in the properties of the members of particle 'ZOO' $\Rightarrow$ Smaller number of constituents: quarks.

Nobody could till then break up the protons and neutrons into quarks.

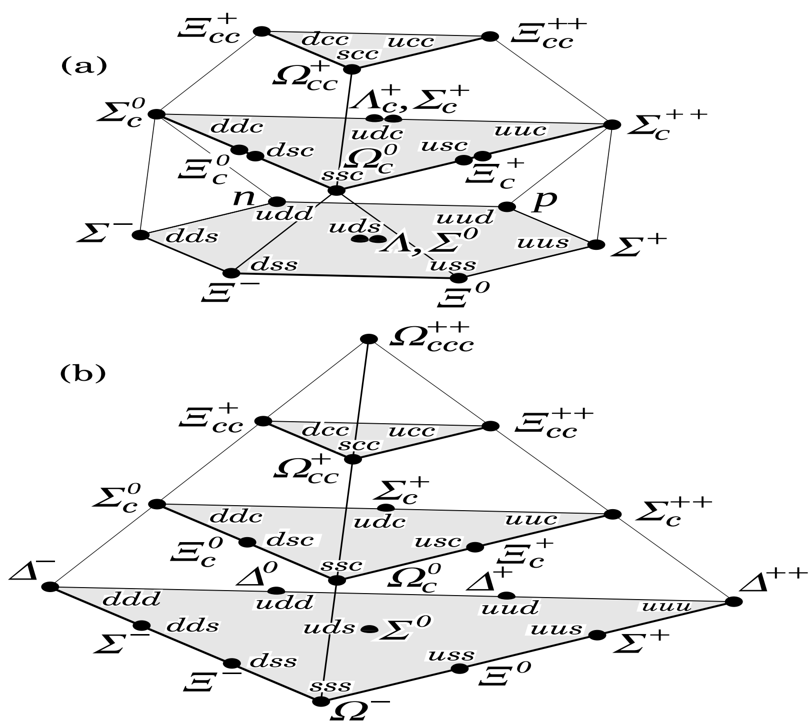
Perhaps quarks were not "real" entities, but some kind of mathematical abstraction.

Worse, they were required to possess fractional electric charges (one-third or two-third the charge of an electron)

Many Physicists decided may be quarks are abstract entities. Just like the Chemists of 19 th century had decided that molecules of a gas, as postulated in Kinetic Theory of gases, were abstract objects.

Even worse: they needed to come in three different varieties, called colour, to avoid a clash with Pauli's exclusion principle!

Gell-Mann's theory predicted existence and mass of a particle called Ω. Confirmed experimentally at Brookhaven. Got the Nobel Prize!



So where were the quarks? Can a Rutherford type experiment see them?

Why do they not appear free in space?

Can we see them when we break open a proton?

How do we break it?

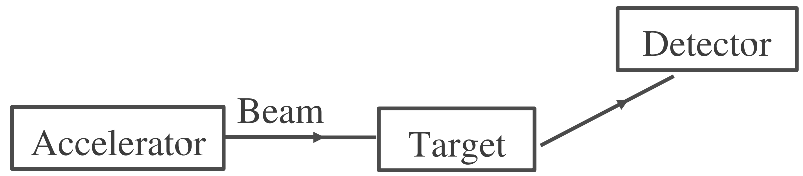
Note the difference from the case of nuclei and nucleons.

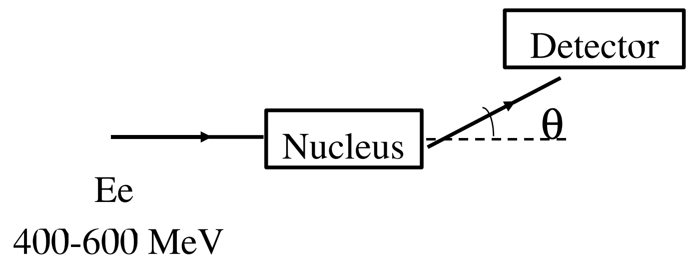
The Hofstadter Experiment: The nucleus/proton version of Rutherford Scattering experiment.

Need higher energy 'beams'.

Development in High Energy Physics went hand in hand with the development in accelerating particles to higher and higher energy.

Stanford Linear Accelerator: S.L.A.C.: 2 mile long accelerator.



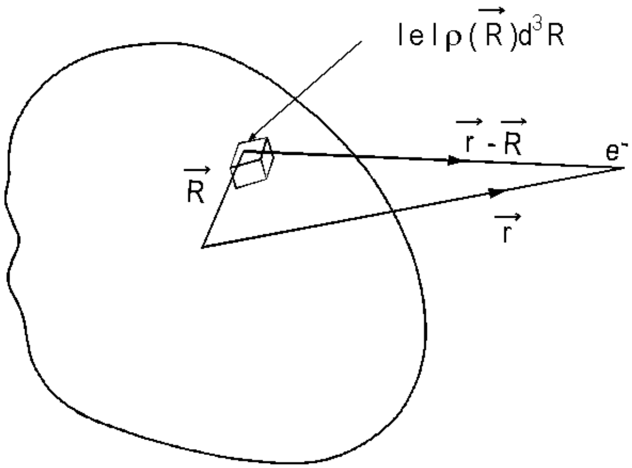


Note similarity with Rutherford experiment.

The $\lambda_e \sim$ a 1000-10,000 times smaller than λ_α.

Count the number of electrons scattered at an angle θ compare it with the number expected for a 'point' nucleus/proton.

from : Interactions.org



The $\frac{d\sigma}{d\Omega}$ is simply proportional to the fraction of incident particles scattered into a solid angle $d\Omega$.

The kinematics of a scattering process is defined in terms of angle θ.

If $\vec{Q} = \vec{p} - \vec{p}'$, normally convenient to use Q^2 instead of θ

If $\rho(\vec{R})$ is the space distribution of the scattering centers one can show that

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{charge distn.}} = |F(Q^2)|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\text{point}}$$

$F(Q^2) = \int e^{i\vec{q}\cdot\vec{R}} \rho(R) d^3\vec{R}$ Fourier Transform of the 'normalised' charged distribution.

Thus spatial distribution will modify the Q^2 dependence compared to the expectation for a point and for a point $F(Q^2)$ will be a *constant*.

In fact it can be shown that at $Q^2 \ll 1/ < R^2 >$,

$$F(Q^2) = 1 - < R^2 > Q^2/6$$

(some factors of Planck's constant $\hbar$ and velocity of light c will have to put in to make the equations look more 'normal')

This then explains why Rutherford found the nucleus to be point like even though we NOW know it to have size of the order of a few fermi's. The energies $\lesssim MeV$ and hence sensitive to distances $\gtrsim 100 - 1000$ fm, much bigger than the nuclear size.

Our ability to infer and study structure of an object from scattering experiments is possible only when $< R^2 > Q^2 \simeq 1$. I.e. smaller the spatial extension higher the energy required.

The Nucleus has a finite size!

The ratio with expectations with a point nucleus, calculated from 'known' dynamics, ~ 1 for $\lambda_e \gg R_{target}$

If $\lambda_e \sim R_{target}$ ratio will differ from 1.

R_{target} is the radius of the nucleus.

Nuclei about 10,000 − 100,000 times smaller than atoms.

Establishing nucleus has finite size which was to be expected because it consisted of nucleons.

WHAT ABOUT THE PROTON?

Proton had gyromagnetic ratio (5.58)*very different* from the value 2 that of an electron.

For any spin half charged point particle it should be 2 according to the Dirac equation (the relativistic wave equation for a spin half particle :later)

Neutron which is neutral should have no magnetic moment at all, but has magnetic moment = -1.91$\frac{|e|}{2M_p}$

This already implied proton and neutron must be at least charge distributions

Can we get information on the spatial extent of these distributions?

Hofstadter studied:

$$e(E_e) + p \rightarrow e(E'_e) + p$$

Energy, momentum conservation tells that for a given E_e and θ there will be a fixed value of E'_e

$$E_0 = \frac{E_e}{(1+2E_e/M_p \sin^2(\theta/2))}$$

Finite size of the proton was confirmed by the scattering experiments (just like nuclei). Size $\sim$ 100,000 times smaller than an atom: a fermi. Is it just a charge distribution OR is there something inside?

The real surprise came when E_e was increased even further!

Process studied:

$e^- + p \to e^- + X$

X $= \pi, K, p, \bar{p}...$; sum over all X. (Inclusive cross-section)

Deep Inelastic Scattering (DIS).

Increase E_e to 10,000 – 20,000 million electron volts. Resolution 1/100 compared to the size of the p/n.

E_e' for a given angle of scattering had many different values and not just one single value E_0. May be the p had something inside it.

At still higher values of E_e the scattered electron again began to have a unique value E_0', different from that for a proton E_0. $\Rightarrow \lambda_e$ small enough to feel the individual scatterers inside the proton.

Scattering at larger angles than possible if proton did not have a structure

The exact value of E_0' in this case could be used to extract their number, which was found to be three.

This is what Gell-Mann's model needed. The quarks thus made a second coming!

Measuring the e energies for different angles, the spin of the scatterers could be determined. These seemed to have all the properties as required by Gell Mann's Quark Model: even the funny charges!

Using ν, μ beams even more information could be obtained!

These quarks seem to have a dual nature: they were glued so well in a proton they did not come out of it when hit by an energetic electron, but the scattering experiments indicated that inside the proton they were almost 'free'.

Theorists were making progress in writing gauge theories of such quarks, if they were to be real physical degrees of freedom! Simultaneous development of Quantum Chromodynamics :QCD, which required 'gluons' and were able to explain why quarks are 'almost' free (asymptotic freedom)

The experiments at the same time showed that there existed scatterers inside the proton, which can not 'see' the electron as they are neutral! This was the first glimpse of the 'gluons' and first clue to the right theory of strong interactions!.

This indirect evidence then confirmed by 'direct' observation of gluons later at DESY. (come to that later)

Increase the energy E_e further, the number of constituents goes on increasing. More and more quarks and gluons are created inside the proton, when one tries to probe it with higher and higher energy.

The increasing energies do not reveal any new constituents but reveal only this increasing number of quarks and gluons inside.

DIS experiments:

S.L.A.C. : 20 GeV (1966-1970)

Fermilab: Neutrinos and muon beams: 500 GeV

CERN: Neutrino and muon beams: 200-300 GeV

DESY: 800 GeV protons on 27 GeV electrons: equivalent to around 50 TeV e^- beam energy (1988-2007)

The highest energy e's $\sim E_e = 50,000$ GeV no evidence for any substructure of a quark up to a 1000$^{\text{th}}$ fermi.

What have the experiments yielded : Very accurate information on $f_{q/p}(x, Q^2)$: probability that a constituent $q = g, u, d, s, \bar{u}, \bar{d}, \bar{s}..$, carries a fraction x of the momentum of the proton, where the scale probing the proton structure has a value Q^2. The ... in above stand for all the remaining (heavier) quarks.

This is what now we use to make predictions for the LHC.

So far we have discussed how we 'discovered' : Leptons e^-, ν, μ; Quarks u, d, s and Gauge bosons γ, g.

YES we think so!

Are we saying this simply because we don't have high enough energy probes? No.

This is where the dynamics, comes into play with full strength. Scattering (or equivalently "seeing") of the constituents only *one* way in which we hunt for what is at the heart of the matter.

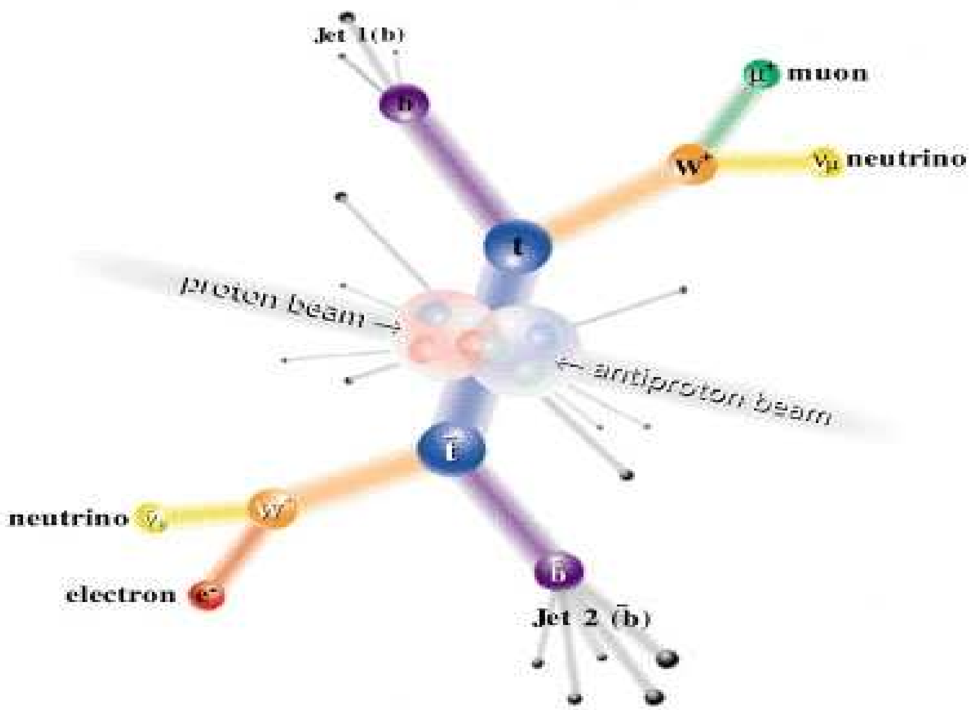
At present every single piece of experimental observation agrees to a very high accuracy, better than to one part in a 100 Millions at times, with the predictions of a theory which treats these quarks and leptons as point-like in the calculations up to energies $\sim 10^{18}$ GeV .

Thus we have "indirect" *but very strong* indications that the quarks and the leptons are indeed point-like and have no further substructure.

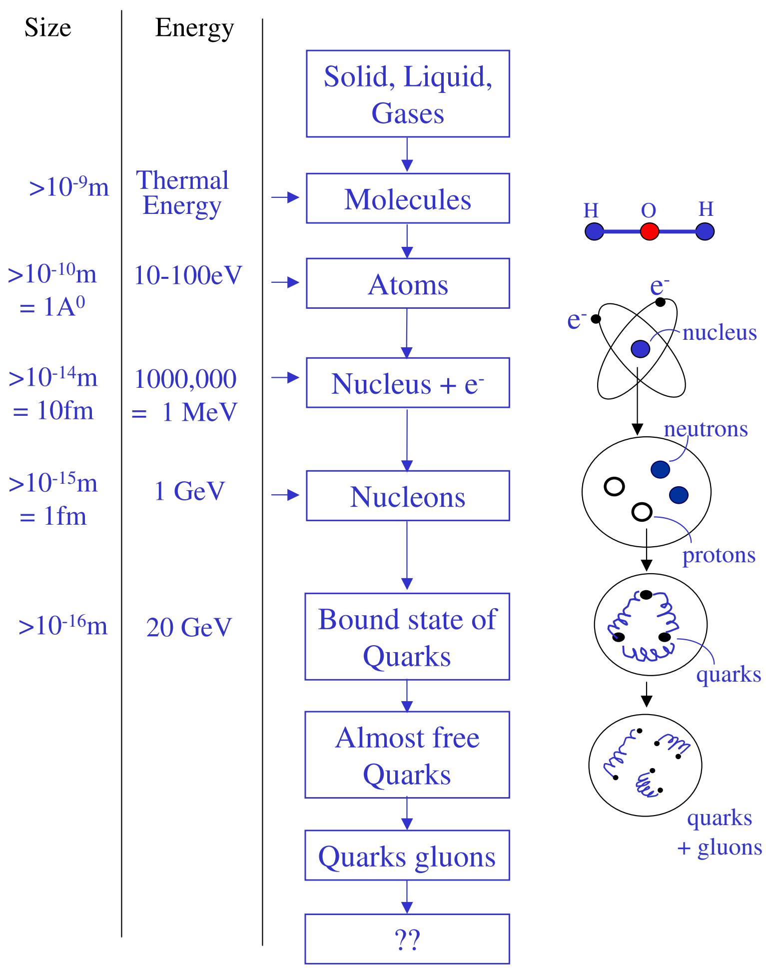
Once one has an understanding of the dynamics of the fundamental constituents i.e interactions among them, one can perform high energy experiments where these scatter off each other, shedding light on

1)The way these interact with each other

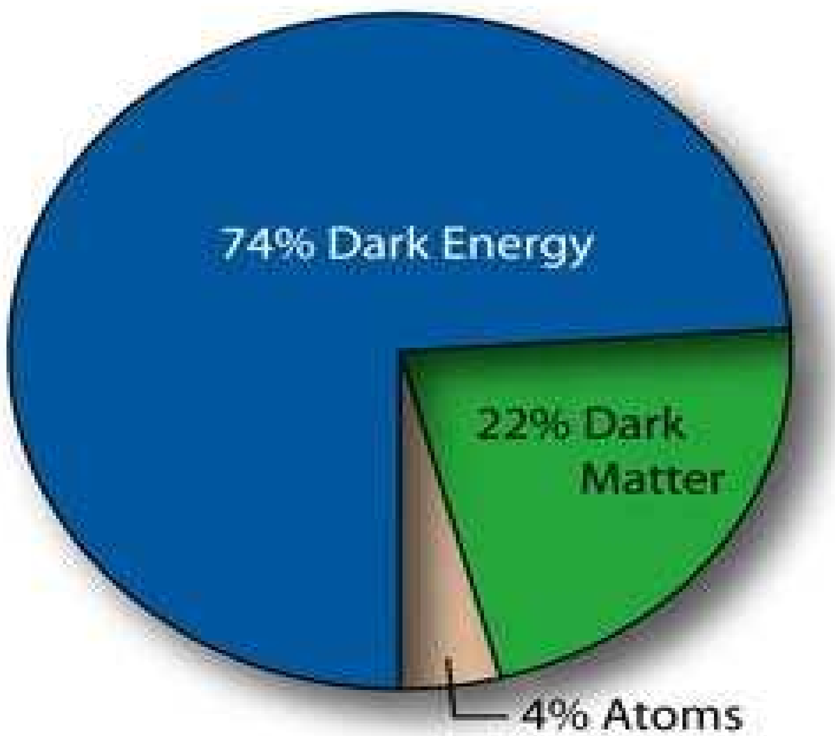
2)Give information on substructure if there is any.



ADDITIONAL SLIDES



The notion of what is elementary is decided by what is the resolving power of the probe and hence the energy/distance scales involved.



The basic features of the three fundamental interactions has a bearing on issues cosmological

1] The contents of our periodic table seem to account for ONLY 4% of the matter in the Universe! Astrophysical evidence pretty convincing.

Dark Matter: experimental information indicates at least one particle beyond the SM (BSM). We can draw this conclusion ONLY because we understand the interactions that *ALL* the SM particles have.

2]Why do we exist? Early Universe in principle has equal matter and antimatter. But Universe of today seems to have a matter-antimatter asymmetry. **An explanation of this asymmetry,** *in the Universe* **in terms of** *known* **properties of the SM particles (CP violation),** *measured in laboratory*, **is possible.**

$N_B/N_\gamma \sim 6.1 \times 10^{-10}$ and $N_{\bar{B}}/N_\gamma \simeq 0$

A quantitative explanation indicates need of Physics beyond the SM. This BSM physics can be studied at the colliders.

3] How was everything formed?

How did the nucleons form? Can we explain the relative abundance of different elements in the Universe? (stars, galaxies...)

These questions are understood in terms of known physics of the SM!!

So laws of particle physics which we have found to be functioning at distance scales of fermi's and smaller, seem to be of relevance in addressing things that happen on cosmological time (say beginning of the universe) and astronomical distance scales (millions of mega parsecs and above!)

If the nucleus is made up of nucleons and nucleons made of quarks why did Rutherford 'see' the nucleus as a 'point'?

How do we measure 'sizes' of objects? How do we resolve them into their constituents?

A small digression:

γ behaved as a 'wave' and a 'particle' $\Rightarrow$ De Broglie : Same is true for the electron too! the wave particle duality.

$$\lambda = \frac{h}{2\pi p},$$

Microscopes were used to 'see' things. Resolving power is higher, smaller the wavelength.

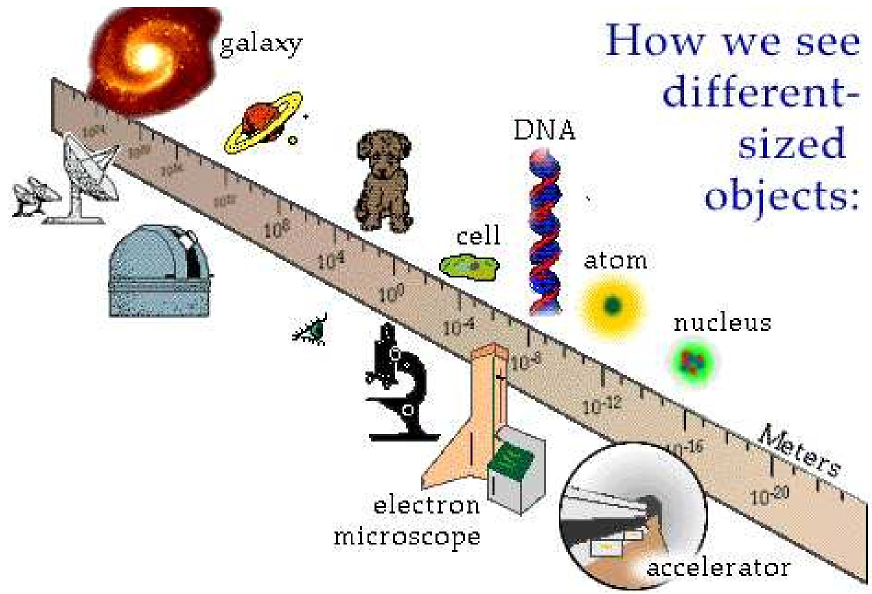
Use high energy particles to 'see' things. Higher the energy, shorter the wavelength, better is the resolution.

Rutherford used α particles to 'look' inside the atom.

the α particles had energy $\sim$ MeV, wavelength $\sim \frac{1}{100}$ Angstrom.

It could therefore 'resolve' atom into nucleus and electrons.

The nuclear size is smaller than this resolution.



High energy particle beams $\simeq$ a meter stick Measure the size by scattering the beam off the object.

Resolving power: De-Broglie wavelength length High energy scattering experiments $\simeq$ putting an object under microscope.

Higher and higher energies to probe smaller and smaller distances. 'elementary particle physics' is $\sim$ 'high energy physics'.

The tools we use to measure sizes of objects changes with the size that they have!

Logical sequence of steps leading to the structure of matter.

1. Seek the regularities/patterns in properties such as masses, spins etc. Very often these reflect *possible* existence of a more basic fundamental units which makes the whole

2. Measure the "size" of the constituents, which at the level of atomic distances and smaller, is simply doing scattering experiments using beams of higher energy particles to get probes of shorter and shorter wavelengths: example at the atomic level of this is Rutherford's experiment

3. A parallel and necessary step is also the development of a theory of the dynamics that holds these units together. See if the observed properties of the composites agree with the predictions of the theory