The Quanta to Quarks module

- The Quanta to Quarks module ultimately deals with some of the most fundamental questions about the universe, such as:
  - What is the nature of the universe and what is it made of?
  - What are matter, energy, space, and time?

- Throughout human history, scientific theories and experiments of increasing power and sophistication have addressed these basic questions about the universe. The resulting knowledge has led to revolutionary insights into the nature of the world around us. This knowledge is an important part of our civilizational background and the driving force of the technological progress.
The Quanta to Quarks module

Therefore, it is highly desirable to introduce elements of this knowledge to high school students.

Challenge: the subject is rather complex and intricate to be fully and rigorously introduced to high school students.

Questions: What to teach? How much to teach? How to teach?

The focus of this presentation:

(i) explanation of basic concepts behind the notion of quanta, i.e. minimal elements of quantum mechanics and special relativity.

(ii) presentation of a modern description of microscopic world, known as the Standard Model of elementary particles
Atoms in classical physics

- Atoms are electrically neutral particles of typical size

\[ R_{\text{atom}} \sim 10^{-11} \text{ m} = 1/10,000,000,000,000 \text{ cm} \]

First photograph of atom’s shadow taken using laser light (Image courtesy Kielpinski Group, Griffith University)

- All material objects consist of atoms
Atoms in classical physics

Periodic Table of Elements

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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Atoms in classical physics

In 1911 Ernest Rutherford has performed his well-known gold foil experiment in which he demonstrated that atom has a tiny, massive nucleus with a size \( \sim 10^{-15} \text{ m} \) smaller than the size of atom.

\[ R_{\text{nucleus}} \sim 10^{-15} \text{ m} \]

Thompson vs Rutherford model of atom
Atoms in classical physics

- **Suggested classroom activity:** Calculate how energetic an alpha particle must be in order to reach the surface of a gold nucleus in a head on collision (use classical mechanics).

\[ E_{\text{alpha}} = \frac{m_{\text{alpha}}v^2}{2} \]

Charge of a gold nucleus = +79e (e=1.6*10^{-19} C is magnitude of an electron charge); Charge of an alpha particle = +2e; Alpha particle must have enough energy to overcome electrostatic repulsion from golden nucleus:

\[ E_{\text{alpha}} = 2e \times 79e \times \frac{1}{(4\pi\varepsilon_0)R_{\text{nucleus}}} \approx 31 \text{ MeV} = 31 \times 10^6 \text{ eV} \]
Atoms in classical physics

- Rutherford’s model nicely explains the periodic table of elements if one assumes that nuclei are compound of 2 type of particles with almost the same masses:
  - Protons with charge $+e$
  - Neutrons which are electrically neutral
  
  \[ m_{\text{proton}} \approx m_{\text{neutron}} \]

  This follows from the observation that for most of atoms the atomic mass number $A$ of nuclei is a bit more than twice the atomic number $Z$

- In 1932, James Chadwick experimentally discovered neutron in series of Rutherford-type of experiments and observing a neutral radiation which was not electromagnetic (photons).
Atoms in classical physics

- **Problem:** The laws of classical mechanics predict that the electron will release electromagnetic radiation while orbiting a nucleus. Because the electron would lose energy, it would gradually spiral inwards, collapsing into the nucleus. This atom model is disastrous, because it predicts that all atoms are unstable.
Atoms in classical physics

- **Problem:** Also, as the electron spirals inward, the emission would gradually increase in frequency as the orbit got smaller and faster. This would produce a continuous smear, in frequency, of electromagnetic radiation. However, late 19th century experiments with electric discharges have shown that atoms will only emit light (that is, electromagnetic radiation) at certain discrete frequencies.
Atoms in classical physics

- Suggested classroom activity: The Larmor formula gives the power \( P \) radiated by a particle of charge \( e \) with an acceleration \( a \). Estimate how much time for an electron in a hydrogen atom to radiate away all its kinetic energy (assume electron moves on a constant orbit \( R \approx 10^{-11} \text{ m} \)).

\[
P = \frac{e^2a^2}{6\pi\varepsilon_0c^3} \quad \text{Larmor formula; } a = \frac{v^2}{R} \quad \text{centripetal acceleration; } m_ea = \frac{e^2}{4\pi\varepsilon_0R^2} \quad \text{Newton’s 2\textsuperscript{nd} law; } m_ev^2/2 = P\Delta t
\]

\[
\Delta t = \frac{12\pi^2\varepsilon_0^2m_e^2R^3c^3/e^4}{10^{-13} \text{ s} !!!}
\]

These problems indicate that the rules of classical mechanics are not applicable to atomic physics!
Quantum mechanics: particle-wave duality

- In classical mechanics we distinguish two types of material object which can propagate and carry energy: particles & waves

\[ p = mv \]

Has definite position in space; definite momentum \( p = mv \); definite energy, e.g., \( E = \frac{mv^2}{2} \)

Waves have no definite position; definite momentum \( p = \frac{E}{V} = \frac{E}{\lambda \nu} \)

- Quantum mechanics: There is no fundamental distinction between wave-type and particle-type motion. Quantum mechanical object in some situations behaves as a wave and in others as a particle
Quantum mechanics: particle-wave duality

- Particle-wave duality was first postulated by L. de Broglie. This unusual phenomenon is incorporated in the rigorous mathematical formulation of Quantum Mechanics (Schrodinger, Heisenberg,...)

\[ p = \frac{h}{\lambda} \]

\[ h = 6.6 \times 10^{-34} \text{ m}^2\text{kg/s} \] - introduced by M. Planck to describe black body radiation

Caution: quantum mechanical waves are not like classical waves. They actually represent probability amplitudes to find a particle with a given momentum in a definite position.
Quantum mechanics: particle-wave duality

- An important consequence of Quantum Mechanics is the uncertainty principle (Heisenberg)

Waves: definite momentum $p = \frac{h}{\lambda}$, indefinite position $x$

Localised pulse: definite position $x$, indefinite momentum $p = \frac{h}{\lambda}$

Momentum and position cannot be measured simultaneously with an arbitrary accuracy: $\Delta x \Delta p \geq \frac{h}{2\pi}$
Atoms in quantum mechanics

- Apply QM to the Rutherford atom:

  Thus electron waves propagating along the stable orbits must satisfy condition:

  \[ 2\pi R = n \lambda, \quad n=1,2,3... \]

  Use \( p = h/\lambda \) \[ pR = n h/2\pi \] (Bohr postulate)
Atoms in quantum mechanics

Since the allowed orbits are discrete, atoms can emit (absorb) only electromagnetic radiation of specific frequencies (explains spectral lines)

- Suggested classroom activity: derive Balmer’s formula from the quantum mechanical picture of hydrogen atom
Quantum mechanics + Special relativity

- Special relativity relation between energy and momentum

\[ E^2 = p^2c^2 + m^2c^4 \]

- Consider massless particle: \( pc = E \) and apply wave-particle duality, \( p = h/\lambda \), where \( \lambda = c/T = c/\nu \):

\[ E = h\nu \]

- This is a quant of electromagnetic radiation introduced by M. Planck to solve the problem of black body radiation and used by A. Einstein to describe photoelectric effect. Corresponding particle carrying this portion of energy is called photon.

**Particle-wave duality is an universal principle!**
Quantum mechanics + Special relativity

Relativistic mechanics

\[ E^2 = p^2c^2 + m^2c^4 \]

Non-relativistic mechanics

\[ E = \frac{p^2}{2m} > 0 \]

\[ E = \pm(p^2c^2 + m^2c^4)^{1/2} \approx \pm(mc^2 + \frac{p^2}{2m}) \] (non-relativistic limit)

- Negative energy particles are interpreted as positive energy anti-particles!
  \[ e^- -- e^+, \ p^+ -- p^-, \ etc. \]

- QM and relativity predict the existence of antimatter!
- C. Anderson discovered \( e^+ \) positron in cosmic rays (1932)
In series of Rutherford-type of experiments it has been established that protons and neutrons consists more elementary particles, named quarks.

- The proton consists of three quarks, denoted as \( uud \), with + sea quarks and gluons.

- The neutron consists of three quarks, denoted as \( udd \), with + sea quarks and gluons.

- The charges of quarks are \( Q_u = +2/3 \) for up quarks and \( Q_d = -1/3 \) for down quarks. Also, quarks carry 3 colour charges.
Sub-nuclear physics – The Standard Model

- Subsequently, there were discovered other types of quarks with exotic names: strange (s, 1953), charm (c, 1974), beauty (b, 1977) and top (t, 1995). They all have similar properties but different masses. Quarks interact strongly by exchange of photon-like particles called gluons.

- Cousins of electron were discovered too: muon (μ, 1947) and taun (τ, 1975). This is so called lepton family of particles.

- Very light neutral partners of charged leptons, called neutrinos (ν_e, ν_μ, ν_τ) showed up in week (radiactive) decays.

- Mediators of week interactions, W^+, W^−, Z^0 (1983) were also discovered.
Sub-nuclear physics - The Standard Model
LHC is the world's largest and highest-energy particle accelerator. It was built by the CERN in 1998-2008, with the aim to address some of the most fundamental question of physics, such as the origin of mass. The LHC lies in a tunnel 27 kilometres in circumference, as deep as 175 metres (574 ft) beneath the Franco-Swiss border near Geneva, Switzerland.
Two beams of protons are accelerated at high energies (currently at 6.5+6.5TeV -- \(\sim 10^{-19}\) m) and then they collide to produce other particles which are detected in detectors in 4 detectors (ATLAS, CMS, ALICE and LHCb)
Large Hadron Collider - World's Most Powerful Microscope

ATLAS detector: 46 m long, 25 m high and 25 m wide.
Weight: 7000 tons

http://atlas.cern/atlas-live
Large Hadron Collider – World’s Most Powerful Microscope

The main result so far: NEW PARTICLE, ~134 times heavier than proton is discovered (4th of July 2012)

It looks like this particle is the missing link in our understanding of the origin of mass – the Higgs boson. An important update to the “periodic table” seems is in order:

2013 Nobel Prize - Francois Englert and Peter Higgs
Quarks

$u, c, t$
$d, s, b$

Forces

$Z, \gamma$
$W, g$

Leptons

$e, \mu, \tau$
$\nu_e, \nu_\mu, \nu_\tau$
What’s Next?
There is overwhelming astrophysical evidence that the universe contains an exotic nonluminous matter (dark matter), which we may be able to detect at LHC!
The masses of lightest Standard Model particles (neutrinos) are not explained by the Standard Model. We may expect new physics phenomena related with neutrino masses to be detected at LHC!
Current measurements of the properties of the Higgs boson indicates that the Universe would be unstable if there is no new physics beyond the Standard Model. Do we live in unstable Universe?
We hope ne learn so much more about the wonderful Universe we live in.
Useful on-line resources:

http://particleadventure.org

http://quarknet.fnal.gov

http://teachers.cern.ch.web/teachers/

THANK YOU