Physics of Beauty:
A window into the known and unknown

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Everyone has a different perception of beauty

In this talk, our focus will be not on any of the 'perceptions' of beauty shown, but rather on a specific particle in the Standard Model spectrum – the b quark and mesons made out of it.

The bottom quark was discovered at Fermilab in 1977. On its discovery, a valiant effort was made by many to name it "Beauty", paired along with "Truth".

The fourth quark discovered in 1974 was named 'Charm' (Up, Down and Strange were already there).

Poetic license gave way to pragmatics, and the quarks were named "bottom" and "top" instead.
Standard Model of particle interactions

* It's a non-abelian gauge theory of strong, weak and electromagnetic interactions (Gravity is not included) - there are gauge bosons (spin 1) mediating the various forces between the quarks and leptons (spin 1/2)

* Higgs mechanism is responsible for mass generation - the physical Higgs particle is missing and one of the most important focus points of present day experiments (also for Large Hadron Collider, LHC)

* Quarks and leptons - fundamental constituents, everything else is made out of them - electron, muon and tau (+ their neutrinos) are the leptons, Constituents of hadrons are the quarks

* We don't see free quarks - QCD, the theory of strong interactions is confining (confinement not understood from first principles) - inside the hadronic bag, the world is quite colourful

Recall: quarks come in 3 colours, but hadrons have no colour
Higgs boson is the only missing piece – crucial to understand the mechanism of mass generation.

LHC is expected to answer this issue.

The Standard Model fundamental particle zoo

Where we stand and what we know

Units used: \( \hbar = c = 1 \)
Perturbative methods are reliable
Thus offer a good playground to test our understanding
Unique systems providing the opportunity to study the
beautiful interplay between strong interaction effects and
other forces at the same time
Importance of heavy quarks – there is more reason..........
Homemade Quark

Recipe

Serves 3 - 222 cal per serving

Prep-time: 10 min. - Total-time: 120 min.

To make homemade quark you will need 2 days. But the actual work time is approx. 10 minutes. This recipe is for about 250 g / 8 oz quark. You can easily double or triple the recipe to make more quark. (for 1 kg / 2 lb., use 4 liters/1 Gallon of milk and 240 ml / 8 oz cultured buttermilk). The texture of the quark depends on how long you drain the quark. The quark is getting drier the longer it drains. You can make the quark smooth again by adding whey or milk. It is important that all utensils you are using are very clean. Pour the milk (best if used 2% or higher) in a big plastic bowl with lid. Add 60 ml / 2 oz cultured buttermilk and stir well. Cover the milk mixture and let it stand at room temperature (22C / 72F) for 48 hours. You will get best results if you don’t move the bowl. After 48 hours you’ve got soured milk (which you can also use). Place the covered bowl on a baking tray lined with a dishtowel. Put the baking tray in the middle rung of the oven. Set the temperature to 30-35 C / 86-95 F and heat the soured milk for about 120 minutes. Now you can see that the whey splits from the quark. The whey has a yellowish-green color. Put the cheesecloth in a strainer and the quark in a bowl. Fill in the quark using a slotted spoon, tie the cheesecloth and hang the quark in a cool place to drain. You can keep the whey for a healthy drink. Enjoy the whey plain or mix in some fruits (like a smoothie), veggies or green tea, just be creative. Store the quark and whey for approx. 5-7 days in the refrigerator. It depends on how cool the room temperature was when the quark was drained.

The heavier, The better

All mass comes from Quarks

Importance of Heavy Quarks -- JUSTIFIED
3 generations of quarks and leptons
Neutrinos are exactly massless
W’s couple up and down partners of each generation while Z and photon are ‘flavour diagonal’
There is mixing between the generations and it leads to CKM matrix in the quark sector
This mixing matrix is a 3x3 unitary matrix (complex elements)- responsible for CP violation within the standard model - has been beautifully tested experimentally
Unitarity of matrix implies relations involving elements from different rows and columns.

Can be represented as Triangles in the complex plane Unitarity Traingles.

\[ V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4). \]

\[ A = 0.8, \lambda = 0.22 \]

Complex part is small (CP violation)
* The elements of matrix $V$ enter the $W$-boson couplings
* Complex elements are responsible for CP violation – till now consistent with all the data
* However, CP violation is also necessary to explain the matter-antimatter asymmetry in the universe
* In the grand scenario, there must be correlation between CP violation that we measure and CP violation required to explain everything else

**Recall**

Beta decay experiments by Madam Wu confirmed Lee & Yang's suggestion that parity is violated in weak interactions

Later Kaon decays showed the CP is also violated
We had to wait for about 37 long years to have the confirmation of CP violation – this happened in B-meson decays

Unlike kaons, CP violation is large in B systems
Symmetries

* Symmetry implies conservation of some quantity and more control and ease in calculations – leads to relations/identities as well
* Can be continuous or discrete - in relativistic theories, continuous symmetries are boosts and rotations while typical discrete symmetries are $C$, $P$ & $T$ (others are permutations etc)

Mirror image = $P$  Black $\leftrightarrow$ White = $C$
Opposite movement of hands = $T$
**CP violation** was first observed in 1964 in kaon decays – the basic reason being that the CP eigenstates are not the mass eigenstates.

We had to wait for 37 years to have a second observation – but this time it was B-mesons.

To achieve this, asymmetric B-factories were constructed – collide electrons (9 GeV) with positrons (3 GeV).

This facilitates to measure the B-meson decay times accurately, allowing study of CP violation – at these machines one basically has the following clean chain:

$$e^+ e^- \rightarrow Y(4S) \rightarrow B\bar{B}$$
Yet another occasion to thank **Albert (and friends)** – this time for EPR

![Diagram of correlated mesons](image)

**$J^P,C$** Quantum Numbers for relevant mesons

$$Y(4S) = 1^{--} \quad B^0 = 0^-$$

Because of the quantum numbers, there is a strict correlation between the two daughter particles. Therefore, identifying one on one side of the experiment, fixes the identity of the other at that time – **Flavour tagging**
Achievements of B-physics experiments

* Expertise in B-tagging was (and is) crucial for picking up top quark signals - led to its discovery in 1994
* 1993 observation of $B \rightarrow K^* \gamma$ played crucial role in searching for top quark in the relevant mass range
* Not just confirmed CP violation and measured other parameters with high precision, B-factories led to discovery of numerous new hadronic states -- Hadron Spectroscopy
Confirmation came via results from B-factories
Theoretical Tools and Techniques

Effective theory construction: Matching, Wilson Coefficients …..

Renormalization, Renormalization Group, Scales and All That: RGE’s

Mixing, scale dependence: An experiment yields a number for some observable quantity - Nature does not care how we, humans, go about calculating this quantity. Presently, perturbation theory is the only available tool in most cases. Eg:

\[ f(x) = g(x(y)) \cdot h(x(y)) = \sum_n g_n y^n \sum_m h_m y^m \]

expanded in terms of auxiliary variable y s.t. product is y independent

Hadronic matrix elements, Factorization…… - Toughest Beast

Need for higher order calculations

* Improve the accuracy of the lower order results
* Stabilize variations against scales * Account for large contributions due to operator mixing
Some Feynman diagrams describing the B-meson decays.
Real Calculations - View from a Distance

Very challenging & time taking. Need heavy computation
Recall: Mass of charm quark correctly estimated from $K - \bar{K}$ and that of top from $B - \bar{B}$ oscillations described by Box Diagram

Penguins were the first flavour changing neutral current processes observed

Serve to be the most important contributions when looking for precision as well as Physics beyond standard model (UNKNOWN)

Such diagrams are sensitive to heavy particles going around in loops - indirect probes of new physics At times, better than other probes

Presence of phases beyond CKM lead to new effects & hence richer phenomenology
A plethora of new states have been found in B-decays – **new era in hadron spectroscopy**

Some of them are a **challenge to the quark model picture** and may actually be the **exotic states** believed to exist in nature.

B-decays allow simultaneous study of electro-weak and strong interactions and involve perturbative and non-perturbative effects at the same/similar level – fantastic testing ground for applicability of our notions of effective field theory.

Resulted in very precise measurements of CKM angles – **confirmed the basic picture of CP violation** – new phases may be present & easily hunted in B-decays.

Already hint at **deviations from SM** – not conclusive at the moment though.

At present **no single model** beyond SM can explain all the (presently not conclusive) anomalies.

Important to revise some SM calculations and include neglected small contributions – hints that these can bring to better agreement with data.

Important field in the LHC era as well – **LHCb**, a dedicated experiment.

If lucky, first clear hints of new physics may emerge soon via B-decays.
Be prepared
Unexpected possible

New direction may prove very bumpy-
We may be forced to change many notions

May even be
Counter-Intuitive

Guidance may come from indirect probes - B-physics is the most important one
Study of B-mesons (hadrons in general) is very interesting in its own right - very important in testing the standard model and beyond

Already provides very stringent constraints on new physics models

An important tool to study electroweak and strong interactions simultaneously

One of the most important Guides in establishing the exact nature of the new physics to be discovered at LHC

Last but not the least, experimental searches have led to discovery of new hadronic states and beautiful progress in spectroscopic studies

Hope to see more beautiful results in future
Anyone who keeps the ability to see beauty never grows old. — Franz Kafka