December 5, 2007

Relativity Classwork 2

Design of a B factory

Introduction

In high energy physics research the present decade is likely to be remembered as the era of the B factories. A "B factory" is a collider experiment optimised to produce B mesons, the lightest particles containing a b quark.

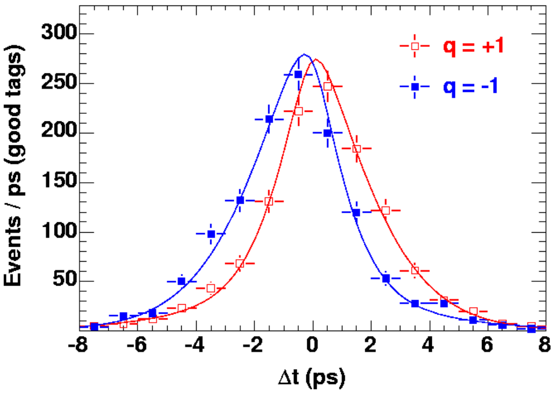

Figure 1: Number of B (■) and $\overline{\mathrm{B}}$ (□) mesons decaying versus time.

The theoretical interest is related to the asymmetry between particles and anti-particles. In the present Universe only matter is observed while we believe equal amounts of matter and antimatter have been created during the Big Bang. Where has all the antimatter gone?

One of the ingredients needed to explain this asymmetry is called "CP violation", defined as a measure of the difference in the behaviour of particles and anti-particles (for instance a different life-time).

A tiny CP violation has been observed in 1964 in the decays of K mesons. The theoretical interest of studying B mesons is that CP violation is very large for these particles, as seen in Fig. 1, where the differences between the B and its antiparticle the $\overline{\mathrm{B}}$ is visible by eye.

B mesons are created in collisions of electrons (e^-) and positrons (e^+). At the appropriate energy the $\mathrm{e}^-\mathrm{e}^+$ collision gives rise to a particle called the $\Upsilon(4\mathrm{S})$ meson, which is the lightest bound state of a b and a $\bar{\mathrm{b}}$ quark allowed to decay to a pair formed of a B and a $\overline{\mathrm{B}}$ meson. The masses and average lifetimes are given below:

Particle		$\Upsilon(4\mathrm{S})$	B & $\overline{\mathrm{B}}$	e^- & e^+
Mass	m	$10.58\ \mathrm{GeV}/c^2$	$5.28\ \mathrm{GeV}/c^2$	$511\ \mathrm{keV}/c^2$
Lifetime	τ	$5 \cdot 10^{-23}\ \mathrm{s}$	$1.53 \cdot 10^{-12}\ \mathrm{s}$	∞

2.1 The CLEO Experiment

The first experiment to create copious amounts of $\Upsilon(4\mathrm{S})$ mesons (several millions) was CLEO at Cornell, USA. The $\Upsilon(4\mathrm{S})$ was created at rest in the laboratory frame before decaying to a $\mathrm{B}\overline{\mathrm{B}}$ pair.

1. Calculate the laboratory frame energy, momentum, γ, β and velocity of the e^- before the collision.
2. Calculate the energy, momentum, γ, β and velocity of the B after the decay of the $\Upsilon(4\mathrm{S})$.
3. What is the flight distance of a B meson decaying after its average lifetime?

The answer to the last question is $\sim 30\ \mu\mathrm{m}$, which is too small to be measured in the experiment.

2.2 Design of the Belle and BaBar Experiments

Since it is crucial to be able to make a lifetime-dependent measurement (as the one in Figure 1 obtained by the Belle experiment) one had to find a way to measure the flight distance. The solution proposed was to increase this distance by not creating the $\Upsilon(4\mathrm{S})$ at rest in the laboratory frame. The B mesons would then have a larger initial momentum and fly a longer distance.

This can be achieved by giving different energies to the e^- and e^+ beams. Detailed simulations have shown that an average flight distance of $200\ \mu\mathrm{m}$ is sufficient. What are the needed energies of the e^- and e^+ beams?

You can make the following approximations:

1. Neglect the e^- and e^+ masses.
2. Neglect the $\Upsilon(4\mathrm{S})$ lifetime.
3. Assume the B is at rest in the $\Upsilon(4\mathrm{S})$ frame. This is justified by the result of Question 2 of 2.1 and avoids the problem that the $\mathrm{B}\overline{\mathrm{B}}$ pair may be produced in any direction which adds an angle-dependent component to the B momentum.

To solve the problem

- Calculate the required momentum p_B of the B mesons.
- Assume the momentum of the $\Upsilon(4\mathrm{S})$ is equal to $2p_\mathrm{B}$ (which expresses assumption 3) and calculate its energy
- Solve the momentum and energy conservation equation for the $\mathrm{e}^-\mathrm{e}^+ \rightarrow \Upsilon(4\mathrm{S})$ collision. Use assumption 1.

You should get approximatively $E_{\mathrm{e}^+} = 8.0\ \mathrm{GeV}$ and $E_{\mathrm{e}^-} = 3.5\ \mathrm{GeV}$, which are the actual values used at the Belle experiment in Tsukuba, Japan.

The competing BaBar experiment in Stanford, USA, chose a larger boost (leading to a longer flight distance). They use $E_{\mathrm{e}^+} = 9.5\ \mathrm{GeV}$ and $E_{\mathrm{e}^-} = 3.1\ \mathrm{GeV}$.