Lancaster Particle Pamphlets

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Fixed Targets and Colliding beams

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Fixed Targets and Colliding beams

Introduction

There are two important ways of carrying out particle physics experiments.

1) Fixed Target

2) Colliding Beam

In the first case a high-energy beam of particles is extracted from an accelerator and made to strike a stationary target. Usually the stationary target is a cylinder containing liquid hydrogen but it may also be solid metal or even a gas. In the early days of particle physics, this was the only kind of controlled experiment available. For example, the proton synchrotron at CERN in Geneva can produce beams of 30 GeV protons and these can be directed at a liquid hydrogen target. In the resulting collisions between moving protons and stationary hydrogen nuclei (protons again) there is sufficient energy to *create new particles*. A typical reaction could produce several pi mesons (given the greek symbol p) and would be written:

$$p + p \to p + p + p^{+} + p^{-} + p^{0}$$

[The pi mesons are either charged or neutral. The electric charges are identical in magnitude to the electron and the sign is given by the superscript]

In the second case two beams of high-energy particles are made to collide head on with each other. This is usually achieved by accelerating particles of opposite charge and equal mass in the *same accelerator*. However, two separate accelerators can be used if particles of the same charge or different masses are used. For example, LEP at CERN produces beams of electrons and positrons that rotate in opposite directions around the accelerator. Each electron and positron has energy up to 100 GeV. The particles are made to collide at four fixed positions and a typical reaction is given:

$$e^{-} + e^{+} \to p + \bar{p} + p^{+} + p^{-} + p^{0}$$

Here the electron e^{-} actually annihilates with its anti-matter partner the positron e^{+} and there is plenty of energy available to create the proton (*p*), the antiproton ($\bar{p}$) and three pi mesons.

Fixed Target Experiments

The general arrangement for a fixed target experiment is shown in Fig.1. I have chosen to illustrate a proton beam hitting a liquid hydrogen target but the arrangement would be the same for any other beam or target. The choice of beam and target depends on the physics process under investigation and on what the accelerator engineers can supply!

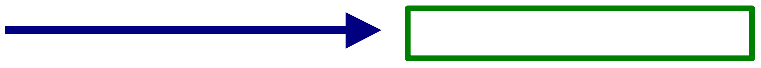

Figure 1

A most important consideration in any particle physics experiment is the energy available to create one or more new particles. New physics most often involves new particles of high mass. For example, the search is now on for the elusive "Higgs Particle". This object may have a mass in excess of 200 GeV/c^2. Consider the case where a beam particle "*b*" strikes a stationary target particle "*t*" and creates a single new particle "X":

$$b + t \rightarrow X$$

(In figure 1 the beam particle would be a single proton and the target particle also a single proton (the hydrogen nucleus)).

A straightforward application of the conservation of total energy and momentum, using the relativistic equations [P1 equation (5)], gives the following formula for the rest mass energy of X . in terms of the beam energy and the target particle rest mass energy:

$$m_X c^2 = \sqrt{2 m_t c^2 E_b} \qquad (1)$$

where E_b is the beam energy and $m_t c^2$ is the rest mass energy of the target particle.

This equation gives the *energy available to create new particles* in a fixed target experiment.

A full derivation of (1) is given in the Appendix.

Dividing both sides of equation (1) by E_b gives a formula for the fraction of the incident beam energy available to create new particles:

$$\frac{m_X c^2}{E_b} = \sqrt{\frac{2(m_t c^2)}{E_b}} \qquad (2)$$

Equation (1) shows clearly that the energy available to create new particles increases only as the square root of the beam energy. Equation (2) shows that the fraction of the beam energy available to create new particles actually *decreases* with the square root of the beam energy.

Example:

A beam of 100 GeV protons strikes a liquid hydrogen target. Find the maximum possible mass of any new particle produced. Repeat the calculation for a 1000 GeV beam.

Use equation (1) to find energy available for new particles:

$m_X c^2 = \sqrt{2\times 1\times 100} \approx 14\,\mathrm{GeV}$

The maximum possible mass for a single particle is then

$m_X \approx 14\,\mathrm{GeV/c^2}$

Using 1000 GeV for the beam energy gives $m_X \approx 45\,\mathrm{GeV/c^2}$.

It is obvious that fixed target experiments are not very efficient in converting beam energy to new particles. We can understand this fact by considering conservation of linear momentum in the collision. The momentum of the produced particle (or particles) has to be equal to the momentum of the beam particle. It follows that the produced particle(s) must have lots of kinetic energy and this is achieved at the expense of the rest mass energy since total energy must also be conserved.

A second important consideration for any experiment is the rate at which any desired process is observed i.e. the number of “events” per second. An “event” is defined to be the observation of a particular collision process, usually one involving interesting new particles or new processes. The *event rate* (R)is controlled by three factors, the *luminosity* (L), the process *cross section* (s) and the *detection efficiency* (e).

$$R = Ls\,e \qquad (3)$$

The luminosity is determined by the intensity of the beam and the number of target nuclei in the target. It is measured in $\mathrm{cm^{-2}\ s^{-1}}$. A typical modern synchrotron can produce a 400 GeV beam of 10^{12} protons per second and if this strikes a 1 m long liquid hydrogen target the Luminosity is $L = 10^{37}\ \mathrm{cm^{-2}\ s^{-1}}$.

The cross-section depends of course on the particular process under investigation. The cross section is measured in cm^2. It represents the effective area presented to the beam particle by the target particle to produce the reaction of interest. The *total* cross section for all strong interaction processes involving 400 GeV protons hitting stationary protons is about $4.2\times10^{-26}\ \text{cm}^2$. This is larger than the actual cross sectional area of a single proton!

The detection efficiency is always extremely difficult to calculate and the experimenter always strives to achieve the maximum possible value 1.0.

Using equation (3), we see that the maximum event rate for our 400 GeV accelerator studying the process $p + p \to$ anything is $R = 4.2\times10^{-26}\times10^{37} = 4.2\times10^{11}\ \text{s}^{-1}$. This is far too large to handle but shows that the method is capable of yielding event rates of around one per second for extremely rare events with cross sections less than $10^{-37}\ \text{cm}^2$.

Advantages and Disadvantages

The main advantages of a fixed target experiments may be summarised as follows

- The event rate can be very high
- The event rate can be acceptable for rare events (provided particles with high mass are not involved)
- The target particles can be readily changed. A liquid hydrogen target could be replaced by deuterium, helium, or heavier nuclei.
- Compared with colliding beams the experiments are relatively easy to arrange.

The main disadvantages are:

- The energy available to create new particles is a small fraction of the beam energy.
- The particles produced tend to have high momentum making accurate measurements difficult.

Colliding Beam Experiments

Most modern particle physics experiments are now conducted using the colliding beam method. This is illustrated in Fig. 2 . This shows a small section of a circular synchrotron accelerator containing beams of particles and anti-particles rotating in opposite directions. Since particles and anti-particles have identical mass and opposite electrical charge they can be accelerated simultaneously in the same machine provided they travel in opposite directions. This can be appreciated if you think carefully about the *directions* of forces produced by electric and magnetic fields on particles of opposite charge moving in opposite directions.

You are probably wondering why the beams don't hit each other as they move around the machine vacuum pipe. This is because the beam intensity is sufficiently small that interactions are very infrequent. However, on either side of the designated *interaction point* (IP) there are powerful quadrupole magnets (Q)that focus the beams down to a very small size. This in turn increases the beam intensity by a very large factor at the IP. The Luminosity of a colliding

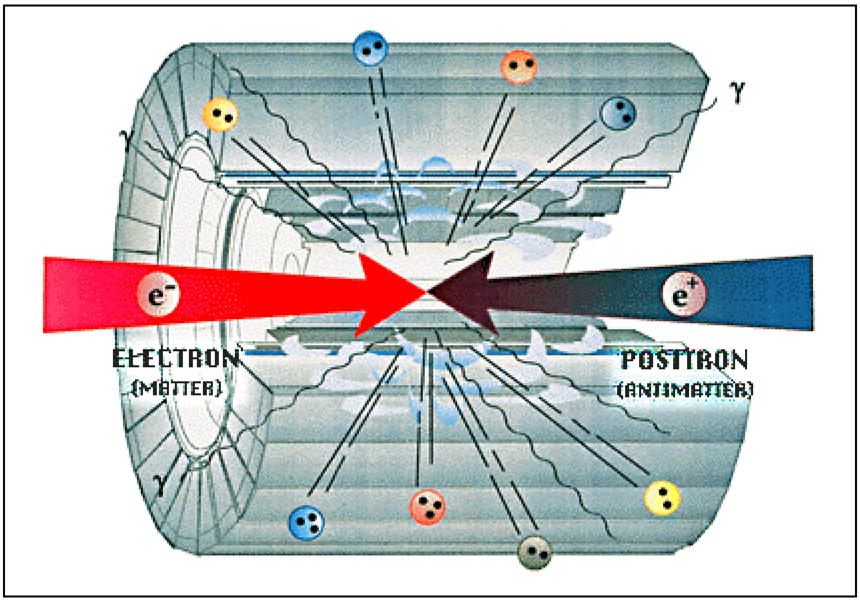

Figure 2

beam machine depends critically on achieving a high intensity in both beams. However, the density of particles in the beams at the interaction point is never anywhere near the density of particles in a solid or liquid target. This means that the Luminosity of colliding beams is always much smaller than a fixed target experiments.

Table 1 gives the beam energies, beam particle types and Luminosities of several modern colliders. Notice the existence of the e-p collider at DESY Hamburg; in this machine, the colliding particles are different and the acceleration has to take place using separate magnet systems and beam pipes. Also the new LHC proton – proton collider being built at CERN will use separate beam pipes.

Name	Beams	Energy / luminosity	Claim to fame
SPEAR (Stanford)	$e^+ + e^-$	1.5 GeV + 1.5 GeV, 10^{30} cm^{-2} s^{-1}	Discovered charm quark and t lepton (1974)
PETRA (Hamburg)	$e^+ + e^-$	15 GeV + 15 GeV, 10^{30} cm^{-2} s^{-1}	Discovered gluon (1979)
SppS (CERN)	$p + \overline{p}$	270 GeV + 270 GeV, 10^{31} cm^{-2} s^{-1}	Discovered *W* and *Z* particles (1983)
LEP (CERN)	$e^+ + e^-$	100 GeV + 100 GeV, 10^{31} cm^{-2} s^{-1}	Confirmed standard model of quarks & leptor
HERA (Hamburg	$e^- + p$	30 GeV + 820 GeV, 10^{31} cm^{-2} s^{-1}	Studies proton structure to distance < 10^{-18} m
LHC (CERN)	$p + p$	7000 GeV + 7000 GeV, 10^{34} cm^{-2} s^{-1}	? starts Higgs particle search in 2004

Table 1

The most important feature of a colliding beam machine is the energy available to create new particles. For particle – antiparticle colliders the energy available is *twice the total beam energy*. This follows from conservation of momentum and the mathematical details are given in the Appendix. Since the beam particles have equal and opposite momentum the total momentum of the colliding particles is *zero* before the collision. The *total* momentum of the created particle (or particles) must also be zero after the collision. It follows that the kinetic energy of the created particle(s) can be zero and *all* the initial energy can be used to create one or more new particles. Consider the case of a beam particle b striking its antiparticle $\overline{b}$ head on, both particles having energy E_b and creating a single particle X:

$$b + \overline{b} \to X$$

$$m_X c^2 = 2E_b \qquad (4)$$

This equation gives the *energy available to create new particles* in a colliding beam experiment

Example:

In 1974 the SPEAR electron positron collider achieved a beam-energy of 1.55 GeV, they were rewarded by copious production of the famous J/y particle. Using equation (4) we find the rest mass energy of the J/y is $2 \times 1.55 = 3.10\,\text{GeV}$ and its mass is 3.10 GeV/c^2. It turned out that the J/y was composed of a quark antiquark pair of a new kind. They had discovered the *charm* quark and started the modern particle physics revolution!

The SPEAR machine is a Stanford Line Accelerator Center in California.

Advantages and Disadvantages

The main advantages of colliding beam experiments may be summarised as follows

- The energy available to create new particles is double the beam energy
- The same bending magnets and focussing magnets can be used to accelerate and control the two beams.
- The kinetic energy and momentum of produced particles tends to be low and easy to measure.

The main disadvantages are:

- The Luminosity is low compared with fixed target experiments.
- The interacting particles cannot be readily changed.
- It is technically difficult to focus the beams to sizes small enough to achieve maximum Luminosity.

Appendix

The energy available to create new particles in a fixed target experiment

Refer to Fig 1.

p_b is the momentum of the beam particle before the collision
E_b is the total energy of the beam particle before the collision
p_t is the momentum of the target particle before the collision $= 0$.
p_X is the momentum of the created particle after the collision
E_X is the total energy of the created particle after the collision

We have

$p_b = p_X$ from conservation of momentum
$E_b + E_t = E_X$ from conservation of total energy

Now use the relativistic relation between total energy, momentum and mass [Eq. 4 from P1].

$$m_X^2 c^4 = E_X^2 - p_X^2 c^2 = (E_b + E_t)^2 - p_b^2 c^2$$
$$= E_b^2 - p_b^2 c^2 + 2E_b E_t + E_t^2$$

but $E_b^2 - p_b^2 c^2 = m_b^2 c^4$ and $E_t^2 = m_t^2 c^4$ since $p_t = 0$
hence $m_X^2 c^4 = m_b^2 c^4 + 2m_t c^2 E_b + m_t^2 c^4$

In most modern applications the squared rest mass energies of beam and target compared with the other terms so that finally we get:

$m_X^2 c^4 = 2m_t c^2 E_b$ and taking square root : $m_X c^2 = \sqrt{2m_t c^2 E_b}$
and $m_X = \left(\sqrt{2m_t c^2 E_b}\right)/c^2$ with units GeV/c^2

The energy available to create new particles in a colliding beam experiment

Refer to Fig 2

For a head on collision between particles b and $\bar{b}$, we have $p_b = -p_{\bar{b}}$ and $p_b + p_{\bar{b}} = 0$.

$p_X = p_b + p_{\bar{b}} = 0$ from conservation of momentum
$E_X = E_b + E_{\bar{b}} = 2E_b$ from conservation of total energy
so that $m_X^2 c^4 = E_X^2 - p_x^2 c^2 = (2E_b)^2$
Hence $m_X c^2 = 2E_b$ and $m_X = 2E_b / c^2$ with units GeV/c^2
