Teaching ideas for Option J, *Particle physics*

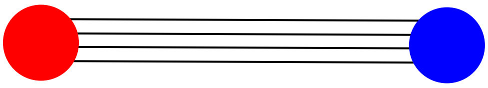
Questions

A number of worksheets are provided for this Option:

- support questions examine the very basic concepts of the syllabus
- extended questions delve deeper and are equivalent to exam level questions.

Teaching ideas

- The CERN site http://education.web.cern.ch/education/Chapter2/Intro.html is an incredible resource, with lectures, slides and videos on every aspect of particle physics and cosmology. It is well worth spending time to find particular topics of interest.
- Very interesting websites with all kinds of information about particle physics can also be found at: http://particleadventure.org/ and http://pdg.lbl.gov/fireworks/intro_eng.swf
- Concentrate on conservation laws and stress that strangeness can only be violated in weak interactions.
- Remember that in Feynman diagrams every vertex is associated with the interaction strength (the 'coupling constant') and so if the interaction constant is less than one, diagrams with many vertices represent processes that are less likely to occur.
- The lines of force between a quark and an antiquark are *not* similar to the pattern of lines of force between an electron and a positron. This explains why the force between the quark and the antiquark is constant and so to separate them by a large distance requires almost infinite energy, hence confinement.



- There are many books and websites on particle physics, but in my opinion one of the most interesting, useful, humorous and entertaining (with amazing first-hand inside stories about the many personalities involved) is the book by one of the greats of particle physics, Martinus Veltman. Veltman shared the 1999 Nobel Prize in Physics with his former student G. 't Hooft. His book is called 'Facts and Mysteries about Particle Physics' (World Scientific, 2003) and is truly wonderful for anyone interested in particle physics. The book by 't Hooft, 'In Search of the Ultimate Building Blocks' (Cambridge University Press, 1997), is also very good!

Case study: Proof of the formula for available energy

People often ask where the formula for available energy comes from. What follows is a derivation, for teachers, using four vectors.

Consider a collision of a 'moving' particle of mass *m* with a particle at rest of mass *M*. In the centre of mass frame the two particles are approaching each other with equal and opposite momenta. Let the 4-momenta of the two particles be *P* and *Q*. Then the total energy *E* is the available energy to create new particles. In the CM frame

$P = (E_1, \vec{p})$ and $Q = (E_2, -\vec{p})$

and so the total energy is

$$E_1 + E_2 = P + Q$$

i.e.

$$E_A^2 = (E_1 + E_2)^2 = (P + Q)^2$$

This is an invariant quantity and may be calculated in any frame of reference. In the lab frame, in particular, we have that:

$P = (E, c\vec{p})$ and $Q = (Mc^2, 0)$

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[I am using the standard 4-momentum notation with metric $(+,-,-,-)$ so that the square of any 4-momentum $P=(E,c\vec{p})$ is invariant and equal to $P^2=(E^2-c^2\vec{p}^2)^2=(mc^2)^2$.]

Thus

$$\begin{aligned}E_A^2 &= (P+Q)^2\\ &= (E+Mc^2, c\vec{p})^2\\ &= (E+Mc^2)^2 - c^2\vec{p}^2\\ &= E^2+(Mc^2)^2+2EMc^2-c^2\vec{p}^2\\ &= (E^2-c^2\vec{p}^2)+(Mc^2)^2+2EMc^2\\ &= (mc^2)^2+(Mc^2)^2+2EMc^2\end{aligned}$$

i.e. the available energy E_A is given by

$$E_A^2=(mc^2)^2+(Mc^2)^2+2EMc^2$$

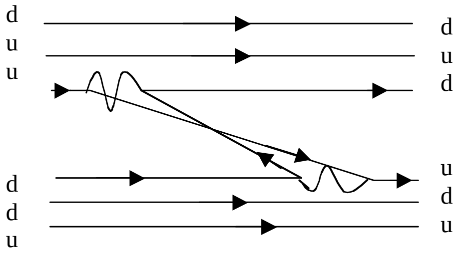
- So in practice we calculate E_A in the CM frame where the least energy needed to create a set of particles is when the particles are created at rest and so E_A is then the sum of the rest energies of the produced particles. We then use the formula above to calculate E, the total energy of the incoming particle in the lab frame.

Practical activities/ICT

- It is not easy to do actual experimental work in this option, but the CERN site has a plethora of activities that can be tried. The site is found at http://hands-on-cern.physto.se/hoc_v21en/

Common problems

- Quarks make up a very large number of particles. Students often ask why we cannot see these particles. It must be said that the great majority of these particles is unstable and so decay as soon as they are formed.
- One item students traditionally have trouble with in this topic is the fact that the strong nuclear force has a short range whereas gluons have zero mass. This takes some explaining! Approaches involve talking first about the electric force between atoms, which is present even though atoms may be neutral. The fact that two atoms are close together implies a change in the distribution of electric charge in the atoms and as a result an electric force (that does not satisfy Coulomb's law) is established.
  For the process p + n $\rightarrow$ p + n show and discuss the following diagram that shows how massless gluon exchange is mimicked by the exchange of a massive pion:



Theory of knowledge (TOK)

- This topic in physics deals with the most fundamental and ancient questions of mankind: 'what is matter made out of?' The quest to answer this question clearly shows a bias on the part of physicists who seem to believe that an answer to this question *must* exist. The reduction of matter to ever smaller constituents seems to agree with this 'bias' so far (molecules $\rightarrow$ atoms $\rightarrow$ nuclei and electrons $\rightarrow$ nucleons $\rightarrow$ quarks). But it is not obvious if this pattern will continue. Worse still it may be technologically impossible to answer the

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question experimentally as the need for higher and higher energies in accelerators may be very difficult to meet.
- It is a phenomenon unique to physics that particle physics (the part of physics studying processes taking place at scales of 10^{-18} m and smaller) joins with cosmology (the part of physics dealing with scales of 10^{26} m) to answer fundamental questions about the Universe.
- The role played by 'beauty' in discovering new results is often discussed in TOK in the context of physics and mathematics. In mathematics, an often heard quote is a saying by G. H. Hardy that 'there is no place for ugly mathematics'. In physics, perhaps the most ardent proponent of the idea of beauty as a guiding principle was Paul Dirac – see Teaching ideas for Topic 6 (AHL).

The power of diagrams: the case of Richard Feynman

Described as iconoclastic, irreverent, arrogant and, above all, brilliant, Richard Feynman is best known in particle physics for his pictorial representation of particle interactions known as Feynman diagrams. He is admired by all physicicts for the three-volume book set known as 'The Feynman Lectures on Physics'. Feynman also became well known to the general public for his part in the investigation after the Challenger Space Shuttle accident. He became quite a cult figure after his death in 1988.

The Feynman diagram represents a particular mathematical expression which is related to the *probability* that the process represented by the diagram will happen. If the diagram contains a loop (i.e. a closed line) then a four-dimensional integral needs to be performed and these integrals tend to be complex and difficult to evaluate. But it still makes the business of finding the probability of the process much easier than without Feynman diagrams. A famous example is the process of a photon scattering off an electron. The details of this process were worked out by Klein and Nishina in 1929 – it took them 6 months. With Feynman diagrams, a graduate student in particle physics can finish the calculation in about 2 hours.

Julian Schwinger, who shared the 1965 Nobel Prize in Physics with Feynman and Sin-Itiro Tomonoga, said that Feynman gave 'calculating power to the masses'. Feynman diagrams show how important imaginative and creative formalism, notation and representation really are in the progress of science.

An incredible book, 'Surely You're Joking, Mr. Feynman!' (W. W. Norton, 1985), a collection of reminiscences by Feynman as he told them to his friend R. Leighton, is a must read for anyone interested in physics.

His Messenger Lectures at Cornell University in 1964 ('The Character of Physical Law') are a must see and they are freely available on the Internet.

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