lines are, however, greatly different. This is not unexpected, since the positronium spectrum is solely governed by the laws of electricity and magnetism, while the charmonium spectrum is governed by the not-as-yet fully understood laws of quantum chromodynamics; this is the name given to the rules which govern the forces between quarks as they exchange gluons with one another†. Naturally, many investigations have been carried out by theorists attempting to fit the new spectra under various assumptions drawing on the analogy with positronium. One exploits this analogy by comparing the simple inverse square law of the electromagnetic interaction that governs the positronium spectrum with the appropriate radial dependence of the force that can account for the charmonium spectrum. This quest has thus far been only partially successful.

9. Beyond charmonium

The spectroscopy of charmonium, analogous to that of positronium, is not the only result from electron–positron annihilation at high energies. History was again to repeat itself as accelerators and electron–positron storage rings moved to higher energy. At Fermilab a fifth member of the quark family, the b quark (b for bottom) was discovered. Subsequently, the combination of the b and anti-quarks—'bottomonium'—was observed in the form of peaking in the yield of various particles as a function of electron–positron annihilation energy at the storage ring DORIS in Hamburg, similar to earlier SPEAR observations for charmonium. Some of the more detailed spectroscopy of this object began to unfold at the Cornell storage ring CESR in the United States. Although these spectra are not as yet as complete as those from the charmed quark states, it is clear that we are again seeing the same basic quantum states as those in positronium. Interestingly, the utility of the spectroscopy as a laboratory to explore the forces acting between quarks increases as the masses of the quark pairs under study increase. The reason is, the heavier the quarks are, the slower they move in the 'quarkonium' combination, and therefore the simpler the theoretical description becomes because the effects of relativity need not be included.

quark and its anti quark

Electron–positron annihilation gives a very direct signature on the number of quarks which contribute to hadronic matter as we know it. By 'hadronic matter' we mean the totality of those particles in Nature, including the neutron and proton and many others, that interact through the strong force; that is, the force we believe to be responsible for binding the neutron and proton in the nucleus. If we recall the diagram of fig. 13, we see that the initial interaction at the first vertex, in which the virtual photon first forms a pair of quarks, is purely electromagnetic. In consequence, the theoretical calculations giving the probability of these reactions is simply proportional to the sum of the squares of the electric charges of each possible quark that could contribute to the process being investigated. As the energy of electron–positron annihilation increases, presumably more and more kinds of quark pairs can be produced, depending on the masses of the quarks and the energy of the annihilation.

Figure 19 describes the present picture of the probability of annihilation of electrons and positrons as a function of energy. What we see are essentially two distinct plateaus separated by a transition region. The arithmetic shows that the first plateau corresponds, at least fairly closely, to three 'flavours' of quarks, while the second plateau corresponds to the addition of a fourth, the charmed, quark flavour. Thus this

† The ideas of quantum chromodynamics and the quark–gluon model are also explained in the article by F. E. Close referred to in the previous footnote.