longitudinal distribution of a bunch affects the length of the interaction region and hence the size of the detectors.

Transversely, the beam growth rate settles down to the predicted gas scattering value after an initial period of about a minute of somewhat faster growth which can be prevented by starting with longer bunches. The bunch length grows from about 2 to 5 ns in a similar period and then stabilizes. The early evolution of these beam distributions is receiving much experimental and theoretical attention.

The backgrounds in the straight section were large and the variations with angle and distance from the beam pipe were measured under various conditions. Integrating the early measurements gave an estimated total flux of 230 MHz through a hypothetical detector of 1 m radius for $10^{13}$ protons in the ring; later measurements, with somewhat better average pressure, correspond to a flux of 84 MHz.

There are indications that the backgrounds are due to high multiplicity events affecting a small fraction of the bunches. The background rate is approximately proportional to intensity (rather than to proton loss rate) and to local vacuum pressure, suggesting an origin in local beam-gas interactions. A bakable vacuum pipe has been installed in the straight section to reduce local pressure and further background reduction will be accomplished by means of vacuum improvements throughout the ring, by shielding, and by beam scrapers.

**Building particles from new quarks**

The observation at Fermilab of high mass enhancements in muon pairs is evidence, though not yet conclusive, for the existence of a new heavy quark (see August issue, page 223).

The study of the spectroscopy of the now abundant charmed mesons has enabled physicists to parameterize the interaction between heavy quark-antiquark pairs and months before the sighting of the Upsilon enhancements by the Columbia / Fermilab / Stony Brook collaboration, E. Eichten and K. Gottfried from Cornell had pointed out that heavier quarks, if they existed, would have an even richer spectroscopy. The structure which already seems to be seen in the Upsilon enhancements could bear this out.

By analogy with the well known positronium bound states of an electron and a positron, these quark-antiquark bound states are often referred to by an ‘onium’ suffix, so that the bound states of a charmed quark and an antiquark (the J/psi family) are examples of ‘charmonium’.

For the lightest quarks (u and d — the constituents of the nucleons), the quark-antiquark binding is not powerful enough to form proper ‘onium’ states but only resonances which decay strongly. For the strange quark (s), the situation is marginal. The phi meson, for example, is only just above the threshold energy for strong decay into KK. If the s̅s̅ binding were a little more powerful, then a ‘strangeonium’ bound state would be seen.

For charmed quarks (c), the masses and binding energies are such that the lowest lying cc bound states cannot decay into a channel which displays ‘naked’ charm. The lightest of the naked charm mesons, the D, has a mass of 1864 MeV, and a charmonium state has to be heavier than 3728 MeV ($2 \times 1864$ MeV) before strong decays into D mesons become possible. Lighter charmonium states, like the J/psi at 3095 MeV, therefore have very high stability (narrow widths) compared with their heavier counterparts and this was the feature which made the J/psi discovery so dramatic.

Since the discovery in 1974 of the first charmonium states, at 3095 and 3684 MeV respectively, the spectroscopy of charmonium has been unfolded by an impressive series of experiments at SPEAR and DORIS.

The new states correspond to higher excitations of the q̅q interaction, to states where the q̅q has rotational angular momentum as well as intrinsic spin, and to states where the q̅q spins line up antiparallel. Quarks with spin $\frac{1}{2}$ can bind together as q̅q states either with their spins parallel (total spin 1), or antiparallel (total spin 0). These latter charmonium states are particularly difficult to observe as their symmetry properties preclude them from coupling directly to a photon and they are therefore seen only indirectly in the decays of the spin 1 states formed in colliding beam experiments.

The interaction between a quark and an antiquark can be simulated by a static attractive potential that is independent of quark mass. Neglecting spin effects, the expected spectrum of bound states can then be calculated using the Schrödinger equation, where the quark mass comes in through a kinetic energy term. The calculated
variation of level spacings relative to the ground state is shown in the diagram.

The shaded region indicates where the 'onium' states can decay strongly into pairs of particles having the appropriate 'naked' new flavour. On the left one sees the spectrum of charmonium with 1s (the psi), 2s (the psi prime) and 1p (the chi) states bound, but incapable of decaying strongly into charmed mesons. The 1d state corresponds to the newly-discovered psi (3772) state just above threshold for production of charmed mesons (see August issue, page 225).

On the right, a quark mass of about 5 GeV shows the pattern of states expected for Upsilon and there are roughly twice as many narrow-width bound states allowed. According to this picture, physics at the new CESR, PEP and PETRA colliding beam machines could contain a richness that will challenge the ingenuity of the best experimenters!

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Cosmic events

Even assuming that all the eagerly-awaited particles such as intermediate vector bosons, Higgs particles and quarks are discovered with the next generation of particle accelerators, this will probably not mean that hadron physics becomes a closed book. Cosmic ray experiments have already hinted that startling new phenomena occur at the prodigious energies reached by the primary cosmic radiation particles.

Since the early 1960s, cosmic ray physicists have been probing the interactions seen in the earth's upper atmosphere with primary particles of energies of hundreds of TeV (1 TeV = 1000 GeV). They think that at about 100 TeV, a bunch of new phenomena could start to appear, in a totally unexpected, and still unaccountable, way.

In contrast with the sophisticated computer controlled experiments mounted in high energy physics laboratories, the investigations of cosmic ray physicists are crude. This is no reflection on the physicists, but simply a result of the nature of cosmic radiation. The incoming particles are randomly distributed in energy, direction and type, and cause primary reactions high up in the earth's atmosphere, producing complicated showers of secondaries. By taking their apparatus to a high enough altitude, on a mountain or in a balloon, the experimenters hope to get as close as possible to the initial primary interactions. Only by collecting the products of these interactions can the nature of the incoming cosmic ray particle be inferred, and even then only approximately.

The detectors used in these cosmic ray experiments are frequently of the 'emulsion chamber' type, in which a specially-designed sandwich of X-ray films and lead plates, extending in some cases over an area of some 40 square metres, is exposed on a suitable mountain site for about a year. The lead plates produce a multiplication of gamma-rays produced initially from the decay of a neutral particle like a pion, and by examining the gamma-ray cascade, the production of neutral pions can be inferred.

Other measurements on the exposed stack enable estimates to be made of the height of the primary interaction above the stack and the total energy in the primary interaction. Because the nature of the incoming primary particle is unknown, this energy is usually given as an equivalent gamma-ray energy — the energy of an incoming gamma ray which would have produced comparable effects.

For interactions whose equivalent gamma ray energies are greater than 100 TeV, the multiplicity of secondaries is found to be much greater than would be expected by extrapolating the behaviour seen at lower energies. At 100 TeV, the highest expected multiplicity on the basis of lower energy behaviour is about 30, while in some cases the observed level is nearer 100.

The number of observed neutral pions on the other hand is remarkably low. One famous example of this is the famous 'Centauro' event seen in the emulsion chamber experiment mounted on Mount Chacaltaya in Brazil by a Brazil/Japan collaboration, in which ninety hadrons are produced with no neutral pions!

The event got its name because the clusters of event seen at the bottom of the detector apparently had the shape of a Centaur — a mythical creature, half horse and half human. Other famous high energy cosmic ray interactions include Andromeda and the Texas Lone Star, both huge lumps of hadronic matter produced by primary cosmic ray interactions in which extremely large numbers of secondary particles are seen.

Whatever the new generation of accelerators will be able to tell us, it begins to look as if hadronic physics could keep on providing surprises as the energy is increased. With unexpected phenomena seen at 100 TeV energies, talk of asymptotic behaviour at laboratory energies seems premature.