

Exotic particles and perhaps new physics?

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The last few years have witnessed phenomenal advances in experimental particle physics. A milestone achieved in accelerator physics was collisions of beams with more than 10^{17} particles/beam/cm²/s. Efficient detectors, better beams and better data analysis have all led to many exciting discoveries. After thirty years of searching, five international collaborations have recently announced strong experimental evidence for a five-quark exotic particle named the theta-plus (θ^+). In April 2003 evidence for a new, narrow resonance (D_s^+ (2317)) with unexpectedly low mass was reported. A 'mystery meson', $X(3872)$ as well as a new, narrow enhancement in proton-antiproton mass distribution have also been sighted. All these new states, which were not as predicted by theory, will provide fresh insight into our understanding of how the fundamental particles bind themselves to form nuclear matter. Apart from these, the B -factories with performance beyond expectations, are providing new data on various B meson decay modes, which will help understand the asymmetry between matter and antimatter. In addition, these experiments are capable of giving a glimpse of physics beyond the Standard Model (SM) of particles and their interactions. In fact, current observations already indicate the presence of such new physics.

The standard model

The fundamental constituents of matter, quarks and leptons, and their interactions are believed to be given by the so-called SM. For each elementary particle there is a corresponding antiparticle with the same mass but reversed charges, electromagnetic, strangeness, etc. Quarks as well as leptons participate in electromagnetic and weak interactions. On the other hand, strong interactions involve only quarks, which carry an additional colour quantum number and are described by a theory known as quantum chromodynamics (QCD). Nuclear matter is made up of strongly interacting hadrons like protons, neutrons and pions, which are in turn composites of quarks. There exist six fla-

vours of quarks—up(u), down(d), strange(s), charm(c), bottom(b) and top(t).

While forces of nature such as gravitation and electromagnetism, increase with decreasing distance between the partners, the attractive force between quarks decreases as they get closer to each other. This feature of asymptotic freedom allows reliable perturbative solutions, at short distances, in the deep inelastic region. However, it is not possible to solve QCD at low energies. Only models which incorporate important QCD aspects can be proposed to explain the hadron spectrum and other low-energy properties. A single isolated quark is never observed; in fact, quarks remain confined to colour singlet bound states, either as bound three quark (qqq) states called baryons, such as nucleons (protons and neutrons) or appear in bound quark-antiquark ($q\bar{q}$) pairs called mesons. Among the mesons are the pions, consisting of the light ud quark-antiquark pair and the mesons with one heavy quark/antiquark: the Kaons (K 's) with an s , charmed (D) mesons with a c and beauty/bottom (B) mesons with a b respectively. A plethora of heavy quark-antiquark mesons like $\phi(s\bar{s})$, charmonium ($c\bar{c}$), upsilon ($b\bar{b}$) resonances have also been observed.

Five experiments discover five-quark particle

The first exception to all observed hadrons being either a bound triplet of quarks or a bound quark-antiquark pair, has finally been found. This new baryon (θ^+) has a mass of about 1540 MeV and a narrow width, limited by experimental resolution. Its observed strong decay (lifetime $\sim 10^{-20}$ s) to a neutron plus a K^+ meson, implies that there is an \bar{s} quark present. Since s quark is defined to have strangeness quantum number $S = -1$, baryons made of three quarks can only have negative strangeness. This state must therefore be exotic, since the fewest number of quarks that could constitute such an $S = +1$ baryon is five.

QCD does not forbid $qqqq\bar{q}$ baryons or $qqq\bar{q}\bar{q}$ mesons. There is indirect evidence of the role of extra $q\bar{q}$ pairs in hadron dynamics. However, a five-quark confi-

guration where the \bar{q} has a different flavour, ruling out annihilation with any of the other four quarks, had not been seen. In fact, why such exotic configuration of quarks never showed up had puzzled physicists. In the words of Maxim Polyakov, a Russian physicist now at the Ruhr University in Germany, 'The absence of these multiparticle states has bothered physicists for the last forty years, now it is over'.

The first experimental evidence for this state was announced by the Laser Electron Photon Facility at SPring-8 collaboration¹ in Japan in October 2002. The LEPS team scattered powerful gamma rays from a fixed plastic scintillator target containing carbon nuclei. It searched for evidence of collisions in which a gamma ray photon interacted with a neutron from the carbon nucleus to produce a K^- meson and a pentaquark, which subsequently decayed into a K^+ and a neutron. A sharp resonance peak was observed at 1.54 ± 0.01 GeV in the K^- missing mass spectrum with a width smaller than 25 MeV. The statistical significance of the signal is 4.6σ .

The next report confirming the θ^+ , came from the DIANA collaboration². A liquid xenon bubble chamber had been exposed to a K^+ beam from ITEP's (Institute of Theoretical and Experimental Physics, Moscow) small proton synchrotron. This group had rescanned an old 1986 film and analysed the effective mass of the K^0p system in the charge-exchange reaction, in which the K^+ produced a K^0 , together with a proton and an unseen recoil nucleus. The spectrum of K^0p effective mass, showed a resonant enhancement centred at 1539 ± 2 MeV and a width less than 9 MeV at an estimated statistical significance of 4.4σ .

The most statistically significant θ^+ peak (with confirmed strangeness) reported to date, came from the CLAS collaboration at the Thomas Jefferson National Accelerator Laboratory, USA³, in May last year. The photon beam produced at the laboratory's electron accelerator, struck a liquid deuterium target and the particles generated were detected. In the final state, a K^- meson and a proton were produced along with a resonance which deca-

yed into a neutron and a K^+ meson. A 5.3σ peak in the nK^+ invariant mass spectrum at 1542 ± 5 MeV with a measured width of 21 MeV was seen. Yet another confirmation of the baryon resonance, θ^+ has come from the SAPHIR collaboration⁴ at the Bonn Electron Stretcher Accelerator ELSA in Germany. The evidence comes from a 4.8σ peak at $1540 \pm 4 \pm 2$ MeV in the nK^+ invariant mass distribution from the photoproduction of the $nK^+ K_s^0$ final state ($\gamma p \rightarrow \theta^+ K_s^0$; $\theta^+ \rightarrow nK^+$; $K_s^0 \rightarrow \pi^+\pi^-$). The upper limit for the width is quoted at 25 MeV.

The most recent evidence for formation of a narrow K_p^0 resonance near 1533 MeV has again been reported from ITEP⁵, where the data collected by several neutrino experiments with big bubble chambers were analysed. Nuclei from hydrogen, deuterium and neon–hydrogen mix in different experiments were exposed to neutrino and antineutrino beams. The combined neutrino and antineutrino data show a distinct enhancement at a mass $m(K_p^0) \sim 1530$ MeV at 6.7σ .

While the pentaquark had eluded previous searches, strong evidence suggesting its existence has clearly accumulated within the past one year. Why was this resonance not seen earlier? The search for baryon resonances with the strangeness quantum number $S = +1$ had been on for a long time. In 1986, evidence for the existence of exotic baryons was reviewed to be poor by the Particle Data Group, wherein a note stated, ‘The results permit no definite conclusion – the same story heard for 15 years . . . likely that it will be another 15 years before the issue is decided’. It did indeed take more than 15 years to discover the first such baryon! A resonance in the 1540 MeV region could not have been found in the earlier scattering experiments as low momenta kaon beams were not available. Moreover, a resonance could have been missed, if it was too narrow (due to gaps in data) or too wide.

Determination of the other properties of θ^+ is not unambiguous and will require further experimental studies. The experiment at SPring-8 was motivated in part by the prediction⁶ of an exotic particle at around 1530 MeV, based on a particular theoretical model of QCD. The model however, also predicted many other unobserved particles. The ‘narrow’ width of θ^+ is puzzling, as it is at variance with expectations from simple kinematics of the decay products.

The number of attempts to explain this new particle is continuously growing in the literature. Apart from non-traditional quark models⁷, there have also been attempts to explain the θ^+ as a KN molecule. QCD sum rules and lattice gauge theory have also been invoked to investigate this exotic particle. The issue can only be settled with future experiments that measure the spin, parity, magnetic moment, etc. of the particle. A study of the shape of the particle will reveal if it is some sort of a bound molecule or a single particle. The numerous models proposed, predict additional associated particles, which if observed, will pinpoint to the correct picture. This will have profound implications for hadron spectroscopy and our understanding of low energy QCD.

Other exotics

In April 2003, physicists at the BABAR experiment at Stanford Linear Accelerator Center (SLAC) in the US, reported evidence for the $D_{sJ}^*(2317)^+$ – a new charmed meson consisting of a c quark and an s quark⁸. Since the mass of this particle is lower than expected, Jonathan Dorfan, SLAC Director said, ‘This result will send theorists back to their drawing boards’. The decay of this meson to a D_s^+ and a π^0 violates the conservation of a quantum number called isospin (I), as all D_s mesons have $I = 0$ and π^0 carries $I = 1$.

The low mass, small width and decay mode of the $D_{sJ}^*(2317)^+$ are in contradiction with the predictions of quark potential models, which have explained spectroscopy of mesons/baryons successfully. Hence, either these models need to be modified, or the state is exotic. Various interpretations of this state are appearing in the literature, which include suggestions that: it might be a four-quark state, a DK molecule, a quasi bound state that arises due to coupling to the nearby DK threshold or is explained by using non-relativistic vector and scalar exchange forces⁹.

The existence of $D_{sJ}^*(2317)^+$ was confirmed by the CLEO experiment at the Cornell Electron Storage Ring, which also observed another similar new state near 2463 MeV¹⁰. The BELLE collaboration working at the High Energy Accelerator Research Organization (KEK) in Japan, has also reported measurements of the properties of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2457)^+$

resonances. BABAR has recently seen the second D_{sJ}^+ resonance as well, at a mass closer to BELLE’s value, both being slightly lower than that measured by CLEO.

At the XXI International Symposium on Lepton Photon interactions, the BELLE collaboration reported a narrow charmonium state at 3871.8 MeV¹¹, now referred to as the $X(3872)$. The mass value is about 60 MeV higher than potential model predictions for a 1D charmonium state. The coincidence of its mass with the $D^0\bar{D}^{*0}$ threshold suggests that this may be a DD^* multi-quark state. This ‘mystery meson’ has also been confirmed by the CDF experiment at the Fermi National Accelerator Laboratory.

Recently, the BES collaboration at the Beijing Electron Positron Collider observed a clear signal for a narrow enhancement in the $p\bar{p}$ mass distribution near the $2m_p$ threshold in the process $J/\psi \rightarrow p\bar{p}$ (ref. 12). The mass and unexpectedly narrow width of the new resonance suggest that it could be interpreted as a ‘deuteron-like’ spin zero proton–antiproton bound state (baryonium), with a zero baryon number.

All of these new exotic states provide an opportunity to refine our understanding of quark dynamics at low energies.

New physics in $B \rightarrow \phi K_s$?

One of the unsolved problems in physics is the observed baryon–antibaryon asymmetry in the universe, which at the very least, implies violation of CP symmetry. CP violation means that the laws of physics change when a particle is replaced by its antiparticle and when all three directions in space are reversed. In the SM, CP violation is parameterized via a complex phase of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, but a fundamental theoretical explanation for its origin is still lacking. Particle physicists are convinced that although the SM explains all the observed experimental results, it needs to be extended. Looking for physics beyond the SM is the aim of studies in particle physics today. While the CKM description does not resolve many mysteries of the SM concerning the flavour sector, yet, the uniqueness of the CKM mechanism, with its single source of CP violation, makes it predictive and testable. The numerous decay modes of the B meson and the CP asymmetries can over-constrain the parameters and help in the search for new physics.

At the asymmetric B factories at SLAC and KEK, a large number of B and anti- B pairs are produced by colliding electrons and positrons at specific energies such that they annihilate to produce the $\psi(4S)$ meson, which decays almost immediately to a coherent state of B and \bar{B} meson pair. The neutral B mesons exhibit the quantum mechanical process of mixing; hence B keeps changing into \bar{B} and vice versa. But once one of the mesons is flavour-tagged (as a B or \bar{B}) through its decay mode, the other one at that point is known to be its antimeson (\bar{B} or B). The distance between their two individual decay vertices is determined by a precision tracking device, which in turn gives the decay time of the antimeson from the time of tagging. The expected CP violation appears as the difference in time-dependent decay rate between that of a neutral B^0 and a \bar{B}^0 into specific final states.

Such a time-dependent CP asymmetry was used to clearly establish CP violation in the B system two years ago by the BELLE and BABAR collaborations. The type of CP violation observed, resulted from the interference of decays with and without mixing. The so-called golden mode $B \rightarrow J/\psi K_s$ was used to measure the sine of twice the $B - \bar{B}$ mixing angle ϕ_1 . This decay mode provides a clean determination of $\sin(2\phi_1)$, without hadronic uncertainties, since within the SM only one weak decay amplitude is possible for this mode. The weak decay of $B \rightarrow J/\psi K_s$ involves no weak phase and the time-dependent asymmetry therefore gives the phase of the mixing alone. The errors in the measurement have since been impro-

ved and the current world average is 0.736 ± 0.049 . This value is in good agreement with the SM expectations.

The time-dependent CP asymmetry of another decay mode $B \rightarrow \phi K_s$, should also yield the same value of $\sin(2\phi_1)$ as within the SM, this mode also has only one weak decay amplitude with no weak phase. A discrepancy between the values of $\sin(2\phi_1)$ obtained using these two distinct modes can appear, if there is some new physics contributing to the decay amplitudes. The theoretical computations of decay amplitude for $B \rightarrow \phi K_s$, show that it is sensitive to contributions from physics beyond the SM. Hence an observed discrepancy in $\sin(2\phi_1)$ can be interpreted as a signal of new physics.

A measurement of $\sin(2\phi_1)$ using the $B \rightarrow \phi K_s$ mode were first reported by BELLE and BABAR about a year ago. Both groups had reported a negative value in contrast to that obtained from the mode $B \rightarrow \psi K_s$. With additional accumulated data, the BELLE collaboration for a total of 140 fb^{-1} (152 million $B\bar{B}$ pairs) reported a 3.5σ deviation from the SM¹³, while BABAR moved closer towards the SM. The average of the two experiments using $B \rightarrow \phi K_s$ is now $\sin(2\beta) = -0.15 \pm 0.33$, still 2.7σ from the SM¹⁴.

To account for this discrepancy, one needs to go to new physics models which are non-minimal flavour-violating, i.e. models which contain more flavour and CP violation than present in the SM. Enormous theoretical activity is taking place to explain the apparent deviation from the SM. However, one has to be cautious and wait for better statistics before concluding that a new physics signal

has been seen. Only a larger standard deviation effect can be taken to be a true signal. The hope, of course, is that the cascade of data coming and expected from the various B -physics experiments will not only reveal new physics, but also provide a powerful tool to discriminate between models of new physics.

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