In Search of Exotic Particles

By XIN Ling (Staff Reporter)

Looking for “exotic matter” is an important task for high energy physics in the post-Higgs era. Using data from the BEijing Spectrometer (BESIII), researchers have observed a family of particles which contain at least four quarks, providing strong evidence for the existence of unconventional forms of matter.

The discovery of Z_c particle family

For Dr. SHEN Xiaoyan, Dr. YUAN Changzheng and their colleagues at the Institute of High Energy Physics (IHEP), Chinese Academy of Sciences, the year 2013 was a fruitful one, as exciting discoveries kept springing up from their old pal – the BESIII detector. In March, they announced the observation of a distinct charged particle, called Z_c(3900), to comprise no less than four quarks, challenging the traditional quark model that says quarks come only in twos or threes. In winter, they went on to report the discovery of Z_c(3900)’s cousins, Z_c(4020) and Z_c(4025), which were spotted in totally different processes and made the previous finding more convincing.

According to the Standard Model, quarks are the basic building blocks of all matter. There are six “flavors”, or types, of quarks and they appear in pairs or triplets. For

Dr. YUAN Changzheng (middle) with his PhD students who made major contribution to the discovery of the Z_c states. GUO Yuping (left) did the Z_c(4020) analysis and LIU Zhiqing (right) did the Z_c(3900) analysis.

instance, a proton is made up of three quarks: two up quarks and one down quark. A pion, on the other hand, is composed of a quark and an antiquark. Within the proton or the pion, quarks are bound to each other via strong force.

To peep into the structure of the subatomic world, scientists have built large facilities to accelerate particles to the speed of light, smash them into each other and study the debris. The Beijing Electron Positron Collider (BEPCII) and its detector BESIII at IHEP is one of such experimental tools. In late 2012, when researchers were using BESIII data samples to study the anomalous Y(4260) particle, they came upon a new particle whose strange characters attracted their attention immediately.

The new particle was observed in its decays into a J/ψ and a charged pion. It weighs four times as much as a proton and carries an electrical charge. "Considering the fact that it must contain a charm quark and an anti-charm quark – the composition of a J/ψ, it must hold at least another two quarks to have a non-zero electrical charge as the pion", explained Dr. YUAN, an IHEP researcher and physics coordinator of BESIII. For instance, a possible composition of Z_c(3900) involves a charm quark, an anti-charm quark, an up quark and an anti-down quark.

BESIII's discovery was soon backed up by the BELLE collaboration in Japan, who declared one week after Beijing's announcement that they had seen exactly the same particle.

"This is a milestone in four-quark object research, because BESIII and BELLE confirmed each other's results. It settled the decade-long skepticism over whether such a structure really exists," Dr. YUAN pointed out.

Following Z_c(3900), more Zc particle family members were brought to light with BESIII, including Z_c(4020) and Z_c(4025).

"Z_c(4020) was discovered using a method very similar to that used in the discovery of Z_c(3900)", according to Dr. SHEN Xiaoyan, BESIII spokesperson from IHEP. Just like Z_c(3900), the Z_c(4020) is electrically charged and decays to a particle consisting of a charm quark and an anti-charm quark and a charged pion. So the interpretation is the same: Z_c(4020) should be a four-quark particle, too. The Z_c(4025) was observed in a very different way, and so far it is still not clear whether it is the same as the Z_c(4020) or not.

"It's very likely that Z_c(4020) and Z_c(4025) are the partner states of the Z_c(3900)," Dr. SHEN added.

The discovery of Z_c particles aroused a lot of interest across the world. "Physicists have resurrected a particle that may have existed in the first hot moments after the Big Bang", a *Nature* article read. At the end of 2013, the discovery of Z_c particles topped *Physics* magazine's "Highlights of the Year".

But the story is far from ending. In April 2014, the LHCb experiment at CERN's Large Hadron Collider (LHC) declared to have confirmed another tetraquark particle, Z_c(4430), which was observed first by the BELLE collaboration . With the Z_c family expanding from 3900 to 4020/4025 and 4430, scientists seem about to reveal a new realm of matter structure.

Understanding Z_c particles

After the initial excitement brought by Z_c(3900), theoretical physicists began to think about the nature of this four-quark particle, hailing it as a discovery "that raises more questions than it answers".

No one questioned the number of quarks in Z_c(3900). However, scientists could not come to a conclusion as for how the four of them are bound together. There are two possibilities. It may be a union of two mesons, each comprising a quark and an antiquark, and the mesons are joined by some loose connection. In this sense, Z_c(3900) is a molecule-like structure.

However, Z_c(3900) could also be a "true tetraquark", in which the four quarks stuck together tightly to form a compact ball. Within the ball, two quarks are bound together and so are the two antiquarks. The advocates of this assumption argued that a two-meson molecule would easily split apart, which has not be detected by far.

If the "true tetraquark" is the case, such a scenario obviously does not fit the classical quark model. Then, does it imply a necessary extension of our existing theories, including the Standard Model?

Not really, in Dr. SHEN's opinion. "While four-quark bound state does pose a challenge to the quark model, it is actually a confirmation of the Standard Model."

The Standard Model is about two important theories: the electroweak theory and the strong force theory, she explained. Under the Standard Model framework, the quantum chromodynamics, or QCD theory gives the best description of strong force. And compared with the quark model, QCD predicts the existence of much more diverse forms of matter, including tetraquarks, pentaquarks, hybrids, glueballs, etc.

"In the past three decades, people have been hunting for these theoretically predicted 'exotic matter', largely in vain. None of them had been observed and confirmed by experiment until the discovery of Z_c(3900). That's why Z_c particles are so important."

A lot more work needs to be done, for BESIII, BELLEII, LHC and other major detectors in the world, to finally settle the debate over the nature of Z_c particles.

"Z_c particles make a typical example of known XYZ particles. It is a window from which we can peep into the world of exotic matter," Dr. YUAN said. In the future, by digging through existing data and conducting new collision experiments, his team will strive to gain a better understanding of observed XYZ particles, and look for new ones.

"Now we are not sure about some of Z_c's characters. For instance, since a Z_c particle can carry a positive or negative electrical charge, as already seen, can we find a neutral Z_c(3900) somewhere? Theoretically speaking, the answer is yes."

Meanwhile, some theories predict that if Z_c(3900) truly exists, there should also be a multi-quark structure made up of a charm, an anti-charm, an up, and an anti-strange quark. Dr. YUAN and his group have started looking for such Z_{cs} particles, using data samples collected from BESIII at 4.6 GeV.

Albert Einstein once said, "As our circle of knowledge expands, so does the circumference of darkness surrounding it." It is so true, especially in unraveling the Z_c mystery.

BESIII: challenges and opportunities

The work on Z_c particles at BESIII was laborious and demanding. A total of 1,500 events were spotted by the detector every second, and the collision went on for a month. After enormous data were collected, scientists conducted software processing and physics analysis to identify a few hundred events that are related to Z_c(3900).

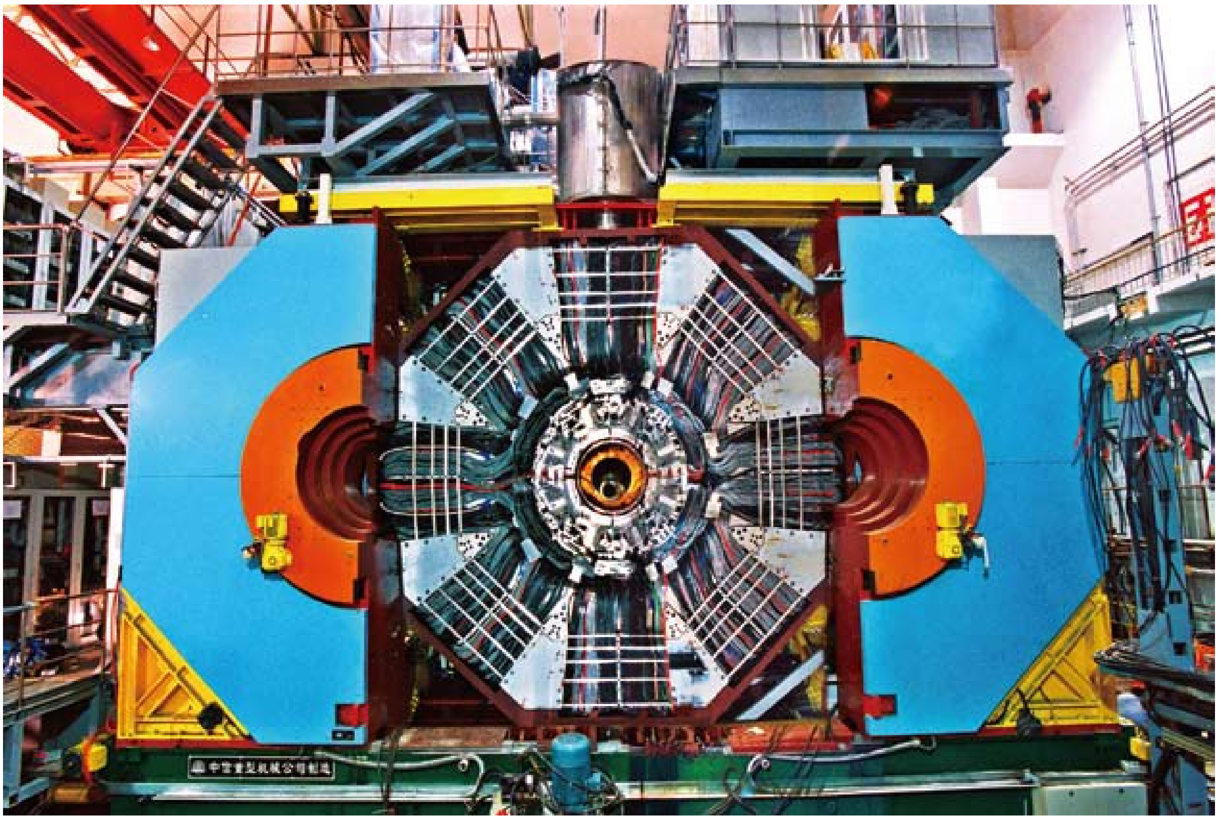
"Thanks to good teamwork among over 400 scientists from 50 institutions 11 nations, BESIII reaped a big harvest in 2013," Dr. SHEN smiled.

Compared with other colliders in the world, BEPCII is only a medium-sized facility running at relatively low energy. Its perimeter is about one hundredth of that of LHC. Luckily, size is not everything for particle accelerators.

"There are two distinct development strategies for colliders in the post-Higgs era. One is to enhance the collision energy to detect particles beyond the Standard Model, like LHC. The other is to examine the details of the Standard Model by improving the collider's luminosity. BESIII goes the second way," Dr. SHEN added.

The road BESIII chose is full of thorns. At low energy

The BEijing Spectrometer (BESIII) at the Beijing Electron Positron Collider (BEPCII), which is installed and operated at the Institute of High Energy Physics, Chinese Academy of Sciences.



region, the experimental and theoretical study of QCD theory is especially perplexing, and is regarded as the least developed part of the Standard Model by far.

"But challenges mean opportunities. We believe BESIII can contribute more to the understanding of strong interaction and to the perfection of QCD theory," Dr. SHEN and Dr. YUAN both agreed.

And IHEP is blueprinting the future of BEPCII and BESIII. In ten years' time, BEPCII will retire and China needs a more powerful collider to consolidate its position in high energy physics.

According to Dr. YUAN, the Chinese Society of High Energy Physics has organized a series of workshops in the last four years to discuss future accelerators in China. There are four options being studied in parallel, including a Circular Electron Positron Collider (CEPC) as a Higgs factory, a High Intensity Electron Positron Advanced Facility (HIEPAF) as a super tau-charm factory, a Circular Z Factory (CZF), and an Electron Ion Collider (EIC). Each machine has its own physics goals and white books are being prepared for further review. Among these projects, HIEPAF is closely related to the study of exotic particles which is the hot topic at BESIII.

"BESIII is a unique experiment in the tau-charm energy region which offers many great physics opportunities. By tuning the energy, many different physics topics can be studied," remarked Dr. Fred Harris, professor in high energy physics from the University of Hawaii, Manoa and former co-spokesperson of BESIII.

So far, BEPCII has not reached design luminosity. "Reaching or exceeding design luminosity would allow collection of data sets more quickly and allow more physics topics to be explored with higher precision. Also integrated luminosity could be increased if BEPCII could do colliding beam physics for more months of the year. I think BESIII has a bright future." Dr. Harris told BCAS.