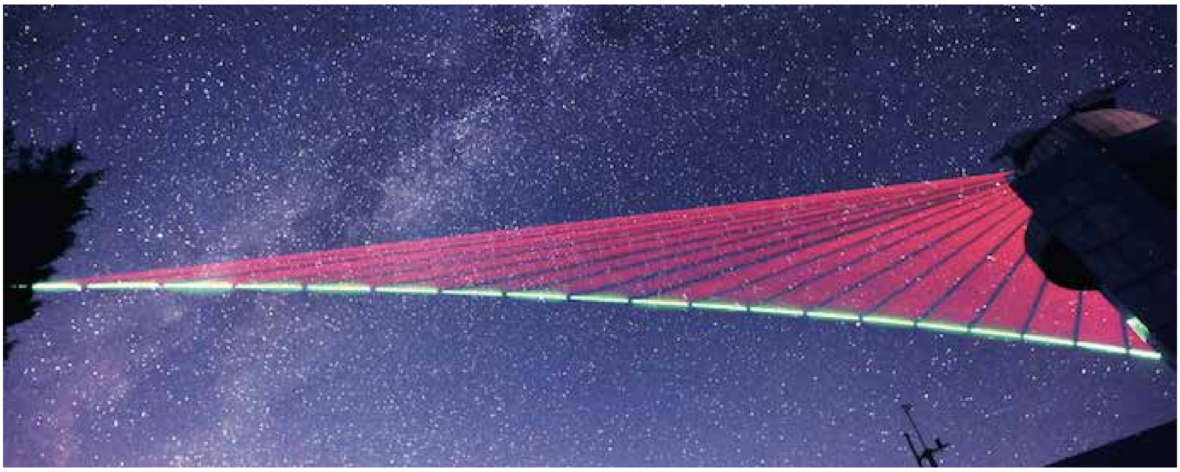
CAS Research Highlighted in "Annual Top 10 Science Advances" 2017

By SONG Jianlan (Staff Reporter)

It is seems to be inevitable. After repeatedly hitting headlines over the year of 2017, "*Micius*," the satellite designed and built by the Chinese Academy of Sciences (CAS) for quantum science experiments at space scale, again drew the attention from the whole S&T circle of China on the morning of Feb 27, 2018, amid the joyful air hailing the Chinese New Year, the Year of the Dog.

This time the satellite was crowned the very top S&T advance of the year 2017, having survived two rounds of ballots by as many as 2,000 illustrious scientists of the country, including Members of CAS and the Chinese Academy of Engineering, chief scientists of projects under the National Basic Research Program (dubbed "973 Program") and directors of State Key Laboratories.



The result from the three major quantum experiments aboard "*Micius*," the first satellite designed by CAS for space experiments on quantum science, reaped the first place of the annual pick of 10 science advances of China. Illustrated here is an image of overlaid time-lapse photos tracking the laser beams to and from the satellite over the Xinglong station, trying to establish a reliable link between the satellite and ground station before the quantum key distribution experiment. The red laser is sent from the ground as a beacon for the satellite to follow and lock on; and the green one, the one carrying quantum keys, is sent from the satellite for the ground station to pick up.
(Photo: By courtesy of Prof. PAN Jianwei's team)

Early in every year since 2005, the annual "Top 10 Science Advances of China" reviews and celebrates the advances made by domestic research institutions over the previous year, aimed at promoting major progress in fundamental research and increasing public awareness of science.

This year the result of the selection released at a good timing to make a nice gift for the 40th anniversary of the "Spring of Science," a collective effort made by Chinese scientists to revitalize science against the trauma and stagnation left by the long-lasting "Cultural Revolution." Early spring of 2018 saw the S&T circle celebrate science excellence at an age of flourishing science, and CAS smile among different research institutions over its own transcript: aside from "*Micius*," four more advances or discoveries made by scientists from the Academy were selected into the "top 10" list, as released by the Chinese Ministry of Science and Technology in Beijing. Remarkably, the first, the third and the fourth places were all taken by advances in the field of basic physic.

Dominating the list, CAS won the 1st, the 3rd, the 4th, the 5th and the 6th places, with its scientists having participated in these winning projects either as principal investigators or major contributors. Topping the list is the results from the space quantum communication experiments aboard "*Micius*," the first satellite designed and built by CAS for quantum science experiments at space scale.

1st Place:

Quantum Entanglement Distribution, Quantum Key Distribution and Quantum Teleportation beyond 1,000 km

Quantum entanglement, a phenomenon in which two quantum particles, say photons, stay in coherence even if they are separated from each other, even puzzled Albert Einstein. Changing either one of the "entangled" pair will lead to certain changes in the other, just like the latter responses instantly to whatever changes in the former. This implies instant transportation of some "interaction" between objects, hence apparently violates the basic presumption of Einstein's Theory of Relativity, in that light always travels at the same speed, regardless of the reference system in which it transmits. All in all, physical actions, for example forces, take time to travel, and nothing can go faster than light.

Yet quantum entanglement evades the law.

Whatever the reason, multiple groups over the world have been competing to triumph on the distance over which the mysterious entanglement could survive between the paired particles. This is not just because the fundamental importance of this physical phenomenon itself, but also its great potential in encrypted communications – if carried by an entangled quantum pair, the key book for a secrete message can never be intercepted, given that any efforts to copy the information coded in either of the particles could immediately destruct the entanglement and hence the information carried, according to a law of quantum physics called "no-cloning theorem."

The survival distance of entanglement matters, because a long enough distance will make it possible to establish a communication path between a satellite and a ground station, and this further will make it possible to connect quantum communication networks scattered across a vast area by satellite-borne repeaters – this, further will pave way for a global network for quantum communications, which theoretically promises absolute information security.

The *Micius* team has scored the longest so far and stayed the record setter, conducting the experiments in the space, to bypass the decoherence caused by the collisions between the messenger photons and the molecules of the dense atmosphere, if conducted on the ground.

Launched on 16 August by a Long March-2D rocket from the Jiuquan Satellite Launch Center in Gansu Province of northwestern China, *Micius* was set to conduct three major quantum communication experiments, respectively for quantum entanglement distribution (QED), quantum key distribution (QKD) and quantum teleportation (QT), all at distances over ~1,200 km, facilitated by five ground stations: the ground station in Xinglong County in Hebei Province, the one in Ali Prefecture of Tibet Autonomous Region in Sichuan Province, the one in the Nanshan Observatory in Xinjiang Autonomous Region, the one in Lijiang of Yunnan Province, and the one in Delingha, Qinghai Province, China – all under the administration of the National Astronomical Observatories, CAS (NAOC).

The team, led by CAS Member Prof. PAN Jianwei, his colleague Prof. PENG Chengzhi from the University of Science and Technology of China (USTC, an educational institution under CAS), and Prof. WANG Jianyu from the Shanghai Institute of Technical Physics (SITP), CAS, reported June 2017 in *Science* and further August the same year in *Nature* the successes of all the preset major experiments.

In their experiments, entangled photons were sent/received by the satellite at an altitude of 500 km above the Earth, to or from two locations situated 1,203 kilometers apart. The summed length traveled by the "spook" varied from 1,600 to 2,400 kilometers.

With aid from *Micius*, the team successfully extended the survival distance of quantum entanglement to a level beyond 1,000 km, from a previous scale of merely hundreds of kilometers. These distances remain the longest to date.

Moreover, they observed a violation of Bell inequality by 2.37 ± 0.09 under strict Einstein locality conditions, strongly indicating that quantum mechanics' explanation of quantum entanglement is right, while Einstein was wrong.

With the successes in QED, QKD and QT over distances of ~1,200$^+$ km, *Micius* has helped remove major obstacles in performing encrypted quantum communications at a space scale. It has demonstrated the feasibility of connecting segments of networks for encrypted quantum communication via satellites to build a global-scale network for ultra-safe quantum communication, protected by theoretically unbreakable encryption.

Nicknamed after *Mozi* (*Mo-tse*), an ancient Chinese scientist who explored pin-hole imaging nearly 2,500 years ago, *Micius* is one of the four science satellites sent into space under the Strategic Priority Research Program on Space Science sponsored by CAS. So far, all the four satellites have been sent into space and have reported successful results.

(For more detail about *Micius*, please go to page 86 of Issue 2 and page 145 of Issue 3, 2017 of *BCAS*.)

Reference:

1. Yin *et al*., Satellite-based entanglement distribution over 1200 kilometers, *Science* 356, 1140–1144 (2017).
2. Liao, S. *et al*. Satellite-to-ground quantum key distribution. *Nature* http://dx.doi.org/10.1038/nature23655 (2017).
3. Ren, J.-G. *et al*. Ground-to-satellite quantum teleportation. *Nature* http://dx.doi.org/
4. Liao, S. *et al*., Long-distance free-space quantum key distribution in daylight towards inter-satellite communication, *Nature Photonics* 11, 509–513 (2017).

3rd Place:

Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

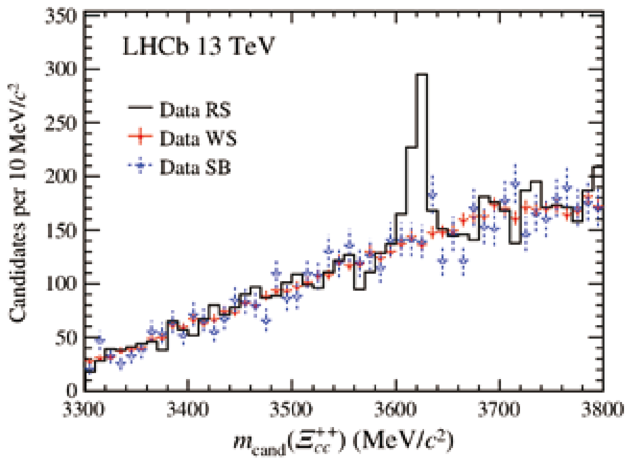
Charming as the prospects heralded by *Micius* are, the winner of the third place is even more beautiful: it is an elementary particle picked up by a "beauty" detector; and it is "doubly charmed."

CERN, formerly known as the *Conseil Européen pour la Recherche Nucléaire* and now the European Organization for Nuclear Research (French: *Organisation Européenne pour la Recherche Nucléaire*), announced on July 6, 2017 that a new type of elementary particle called "doubly charmed baryon" was detected by the "Large Hadron Collider beauty" (LHCb), one of the seven particle physics detectors at its Large Hadron Collider (LHC) accelerator.

Over 1,000 scientists from 16 countries work at LHCb, collecting data for ambitious physics research aimed at explaining why the universe even exists filled with normal matter, rather than annihilating as a result from the collision between matter and anti-matter. Fighting for this beautiful goal, member institutions from China include Tsinghua University (THU), Central China Normal University, University of the Chinese Academy of Sciences (UCAS) and Wuhan University. Headed by Prof. GAO Yuanning from THU, the Chinese team played a leading role in the physical analysis of data from the experiment.

The newly identified particle carries two units of electric charge, with a mass of about 3,621 MeV, which is almost four times of proton's. Similar to the proton and the neutron, the doubly charmed baryon is composed of three quacks, but with different compositions from them: while a proton contains two up quacks and one down quack, and a neutron contains two down quacks and one up quacks, the new member of the family of elementary particles contains two charm quacks, which are heavier than normal quacks, and one down quack.

The scientists identified the spectrum of the state in a sample of proton-proton data collected by the LHCb experiment at a center-of-mass energy of 13 TeV; and confirmed it in an additional sample of data collected at 8 TeV.



Mass spectrum of $\Xi_c^+{}_c^+$ candidates. The LHCb Collaboration detected the particle at a center-of-mass energy of 13 TeV. (Image: American Physical Society)

Theorists predicted that the inner structure of the doubly charm baryon could be different from all the previously found particles, hence research into its properties might help people better understand the structure of matter as well as the nature of strong force, or the strong interaction between elementary particles, like the action tightly binding together proton(s) and neutron(s) in an atomic nucleus.

Reference:

R. Aaij *et al*. (LHCb Collaboration), Observation of the Doubly Charmed Baryon $\Xi_c^+{}_c^+$, *Physical Review Letters* 119, 112001 (2017). doi: 10.1103/PhysRevLett.119.112001

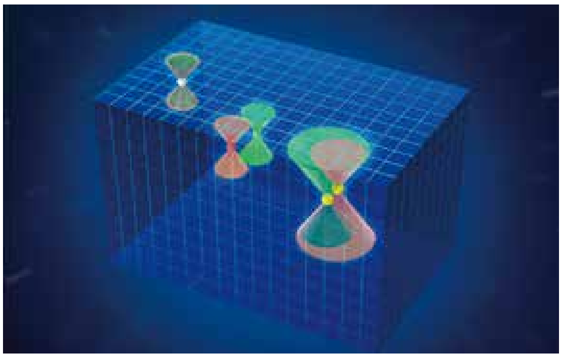
4th Place:

Experimental Observation of Three-Component Fermions

The fourth place was taken by the discovery of a quasi-particle once thought to be nonexistent.

According to the Standard Model, the mainstream theory to explain matter in the cosmos as a result from the Big Bang, the elementary particles of matter can be divided into bosons and fermions. As a result from Lorentz invariance, an effect in quantum field theory, only three types of fermions are possible to exist in the cosmos: the Dirac, Weyl and Majorana fermions. Among them, the Dirac fermion has four components, while Weyl and Majorana fermions two – no fermion of three components exists in the cosmos, the theories said.

Such fermions have been proposed by physicists as low-energy, long-wavelength quasi-particle excitations in condensed-matter systems, whether or not exist in the cosmos. So far, physicists have confirmed in their experiments the existence of Dirac and Weyl fermions in condensed-matter systems, and some results also support the existence of Majorana in such systems. Unlike in the "real" cosmos, in crystals, Lorentz

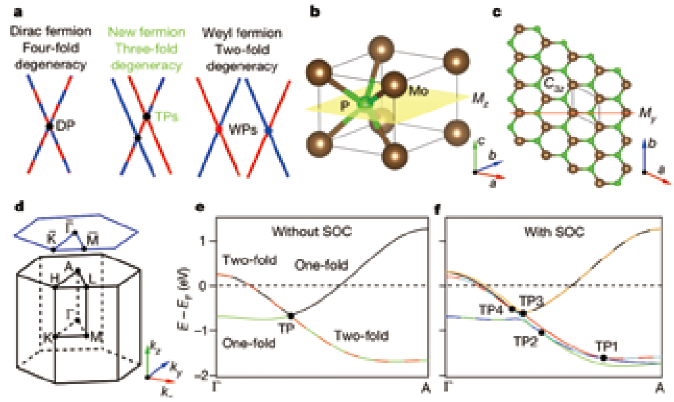


The existence of quasi-fermions in solid materials, or the "solid cosmos." Shown here are three types of fermions, respectively of four (left), two (middle), and three (right) degrees of degeneracy. (Image: Courtesy of Institute of Physics, CAS)

invariance is not applicable due to the special symmetry of the inner space, and this gives rise to the possibility to observe special states that might not exist in the "real" cosmos. Therefore, such condensed-matter systems form a "solid cosmos" where physicists can explore fantastic phenomena otherwise impossible in high-energy physics.

And three-component fermions are among them.

By using angle-resolved photoemission spectroscopy, a team led by Profs. DING Hong, QIAN Tian and SHI Youguo at the Institute of Physics, CAS and their cooperators successfully demonstrated the existence of a triply degenerate point in the electronic structure of crystalline molybdenum phosphide. Such quasi-particle excitations near a triply degenerate point were identified as three-component fermions, a type of fermions beyond the conventional Dirac–Weyl–Majorana classification.



Crystal structure and band structure of MoP along the Γ–A line in the Brillouin zone. a, Schematics of Dirac and Weyl fermions, and the newly discovered fermion, which have band crossing points with four- (Dirac point, DP), two- (Weyl point, WP) and three-fold (triply degenerate point, TP) degeneracies, respectively. b, Three-dimensional crystal structure of MoP. The yellow plane indicates the mirror plane M_z. c, Top view of the lattice showing the C_{3z} rotation symmetry with respect to molybdenum (brown spheres) or phosphide (green spheres) and the My mirror plane (horizontal red line). d, Three-dimensional bulk Brillouin zone (black) and the projected (001) surface Brillouin zone (blue), with high-symmetry points indicated. e, f, Calculated band structures along Γ–A (in terms of the energy *E* relative to the Fermi energy *EF*) without (e) and with (f) SOC. The filled circles at the crossing points indicate the triply degenerate points. The curves with mixed colours represent doubly degenerate bands and those with uniform colour represent non-degenerate bands.

This discovery indicates that crystalline molybdenum phosphide might represent a platform for studying the interplay between different types of fermions. Their experimental discovery opens up a way of exploring the new physics of unconventional fermions in condensed-matter systems.

Reference:

Lv *et al*., Observation of three-component fermions in the topological semimetal molybdenum phosphide, *Nature* 546(7660), 627–631.

5th Place:

Low-temperature Generation and Storage of Hydrogen

Winner of the 5th place might promise a rosy future for the large-scale application of hydrogen as an alternative power supply, by removing a long-existing obstacle in the way.

Hydrogen has been thought to be star of new-generation clean energy source, as the only production from its combustion is water, giving off no pollution. However, its highly inflammable nature makes its storage and transportation a headache: when mixed with air it can easily turn into a strong explosive. On the other hand, its generation is highly energy-consuming.

A smart strategy is to store it in liquid methanol, which stays very stable in transportation. Once arrives at the right place, it can be extracted by a certain reaction between water and methanol. As a bonus, in the process this reaction can even produce extra amount of hydrogen by activating the water to promote its decomposition.

This method, if successful, could be a viable way to exploit hydrogen as power supply for vehicles, given its high efficiency and easiness to integrate with vehicles or, polymer electrolyte membrane fuel cells.

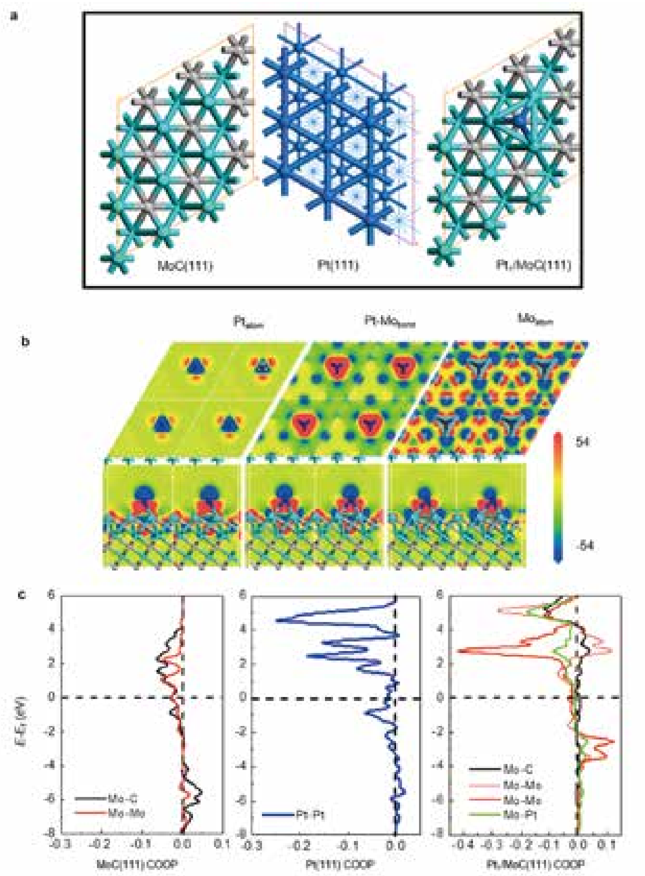
This very vital reaction is called the aqueous-phase reforming of methanol (APRM).

Traditional reforming of methanol steam, however, operates at relatively high temperatures (200–350 degrees Celsius), and application of this reaction in fuel cells demands a robust catalyst.

A team led by Prof. MA Ding from Peking University, Prof. WEN Xiaodong from the Shanxi Institute of Coal Chemistry, CAS and Prof. SHI Chuan from Dalian University of Technology successfully synthesized a catalyst to solve this problem.

They found that platinum (Pt) atomically dispersed on α-molybdenum carbide (α-MoC) could enable low-temperature (150–190 degrees Celsius), base-free hydrogen production through APRM, with an average turnover frequency reaching 18,046 moles of hydrogen per mole of platinum per hour. This exceptional hydrogen production far exceeds that of previously reported low-temperature APRM catalysts.

The water-gas shift (WGS) reaction (where carbon monoxide plus water yields dihydrogen and carbon dioxide) is another essential process for hydrogen generation and carbon monoxide removal. This reaction has certain advantages at a low working temperature.



Calculation models and electronic properties of Pt/α-MoC, a catalyst for low-temperature hydrogen production from water and methanol. (Image: Shanxi Institute of Coal Chemistry, CAS)

Its application in fuel cells, however, also requires a WGS catalyst to promote the reaction into a highly active, stable, and energy-efficient state and to match the working temperature of on-site hydrogen generation and consumption units. The team developed a catalyst to convert CO through its reaction with water into H_2 and CO_2 at temperatures as low as around 150°C. This catalyst, featuring layered gold (Au) clusters on a molybdenum carbide (α-MoC) substrate, is able to create an interfacial catalyst system for the ultralow-temperature WGS reaction. With this catalyst, water can be activated to a high WGS activity at a temperature as low as 303 kelvin (around 33°C).

Reference:

Yao *et al*., Atomic-layered Au clusters on α -MoC as catalysts for the low-temperature water-gas shift reaction, *Science* 357(6349), 389–393 (2017).
Lin *et al*., Low-temperature hydrogen production from water and methanol using Pt/α-MoC catalysts, *Nature* 544(7648), 80–83 (2017). (doi:10.1038/nature21672)

6th Place:

New Crania Unearthed from Xuchang of Henan, China, Indicating Both Regional Continuity and Interregional Population Dynamics of Human Evolution

The sixth place was won by the discovery and research of two specimens of fossil human crania, named Xuchang 1 and Xuchang 2 from Henan Province of China.

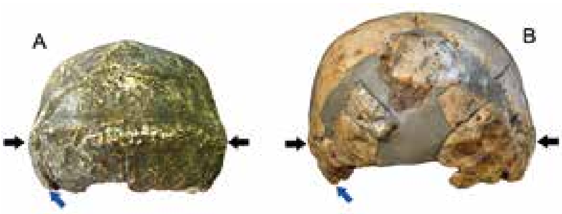
Paleoanthropologists have long puzzled by the evolutional episode of humans in North Eastern Eurasia between the period from about 200,000 to 50,000 years ago, or from late Middle and early Late Pleistocene. The amplification of regional diversity plus the fragmentary status of fossil record from this period and region have thrown this prehistory in mist.

How to evaluate the human fossil unearthed from this portion of strata? Debates have long persisted.

The new crania described in a study published on March 3 in *Science* unveiled some details of human evolution in this period. The two crania, named "Xuchang 1" and "Xuchang 2," as reported by paleontologists led by Dr. WU Xiujie from the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), CAS and their collaborators, were discovered and unearthed from the early Late Pleistocene (~105,000- to 125,000-year-old) strata of Lingjing, Xuchang, China. They exhibit both differences from and similarities to their western contemporaries, like Neanderthals; and show some advanced structures close to modern humans. This combination of features, according to researchers, might reflect Pleistocene human evolutionary patterns in general biology, and mirror both regional continuity and interregional population dynamics.

The newly found crania might represent a new type of archaic human population, whose evolutional niche is yet to determine. Possibility is that there co-existed multiple human populations during that period, with some genetic interaction between each other.

The Xuchang 1 (A, superior view) and Xuchang 2 (B, posterior view) crania. (Image by Dr. WU Xiujie)



Posterior views of the Zhoukoudian *Homo erectus* (A) and the Xuchang 1 (B) cranium. Black arrow showing a low widest point of the vault; Blue arrow showing a short and inward sloping mastoid process. (Image by Dr. WU Xiujie)

(For more detail about the Xuchang crania, please go to page 59 of Issue 1, 2017 volume of *BCAS*.)

Reference:

Li *et al*., Late Pleistocene archaic human crania from Xuchang, China, *Science* 355, 969–972 (2017).