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THE ANTIMATTER HUNTER AMS-02 TURNS 10

Interview with Samuel Ting, Nobel Prize in Physics in 1976 and AMS spokesperson.

Last May 19, the Alpha Magnetic Spectrometer AMS-02, the largest particle detector operating in space, celebrated its 10th birthday. Hosted on the International Space Station (ISS), where it was transported and installed in 2011, the experiment is successfully continuing its scientific mission. The study of cosmic rays, the particles that are messengers of astrophysical phenomena in the Universe, is its main objective. On the occasion of this birthday, we talked to the father of this experiment, the Nobel Prize winner Samuel Ting, who is also the international spokesperson of the AMS-02 collaboration.

How was the project of building a great experiment on board of the International Space Station such as the Alpha Magnetic Spectrometer born?

In the early 1990s, I was working in my garden, and I was thinking, I've been doing particle physics all my life maybe I should do something different, something I know nothing about. Then I remembered, many years ago I did an experiment that discovered the anti-deuteron (a particle made of an anti-proton and of an anti-neutron; ed. the antideuteron was discovered in 1965 independently by a team led by Antonino Zichichi at CERN and at by a team from Columbia University, where Samuel Ting was working, at Brookhaven National Laboratory) and I started thinking: if the universe has come from a Big Bang, at the beginning, there should have been an equal amount of matter and antimatter. So, where is the universe made of antimatter? Hence, I thought I should try to put a magnetic spectrometer into space to try to answer to this question. And that's how this experiment started even if, at that time, I had absolutely no experience with space.

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Was it hard to design and build an experiment to be installed in space with no previous experience in this field? How was the journey that brought AMS-02 in space?

At the beginning, indeed, it was quite difficult because I had no concept that in space weight is very important. On the ground, you can build a spectrometer of thousands of tons but in space, the scenario is completely different. When you lift a kilogram into space, the cost is enormous. Another challenge to bear in mind when designing an experiment for space is that you cannot repair it once it's there.

Fortunately, I had many friends, among them Antonino Zichichi, Roberto Battiston and Bruna Bertucci, from INFN, and many others. So, together with researchers from Italy and INFN, but also from many other countries such as Germany and France, we decided to propose this experiment. So, in 1994, on May 9th, I went to see the head of NASA, Daniel Goldin, and he thought that we were proposing a good experiment that could be installed on the International Space Station, but he also suggested to run an experiment on a space shuttle first, since we had no experience in space. Then, if the space shuttle was successful, we could run the experiment on the International Space Station. So, we built the experiment to be run on the space shuttle very quickly. It took us only over two years to build this experiment, when NASA thought it would have taken ten years. And the experiment flew successfully on the space shuttle. After the success of this first experiment, NASA proposed to install the same detector on the International Space Station. However, we thought it was better to build a super precise detector for the space station and it took us nearly ten years to build this experiment. This is basically how AMS-02 is in space.

The story of AMS is strongly entangled with the history of cosmic rays and particle physics. How has this experiment pushed forward the study of particle physics from space?

Cosmic rays were discovered in 1911 by Victor Hess, who was awarded the Nobel Prize in Physics in 1936. This discovery paved the way to the detection of many elementary particles, such as the positron, discovered by the Nobel Prize winner Carl Anderson and the pion, discovered by Cecil Powell, who also received a Nobel Prize.

Basically, before the development of accelerators, many elementary particles were discovered in space and after the first accelerators were built, many physicists switched their attention to these powerful machines. But now, as the accelerators become larger and more expensive, many researchers are gradually going back to space.

In the past, people went to space using balloons and satellites, but these two methods have some drawbacks. Balloons are only for short-term missions, because at night when the temperature cools down, a balloon tends to go back to the ground, while it is difficult to put a large magnet on a satellite. So, before AMS, there were many experiments taking data from space and most of them could only

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perform measurements at low energies and with large uncertainties (30 to 50%) with the exception of the PAMELA experiment that did a very good work. AMS is a much larger detector, much more precise, and so it allows us to examine cosmic rays with a much higher accuracy. We can see totally different things, as if we are now finally looking at the sky with the telescope rather than with the eye.

What are the main scientific results achieved by the AMS experiment in these ten years of data-taking?
In these ten years, thanks to all the efforts from AMS researchers, from INFN Divisions and Italian Universities of Perugia, Milano, Roma, Trento, Bologna and Pisa together with colleagues from the United States, Germany and many other countries, we have basically changed our understanding of cosmic rays. None of our results agrees with theoretical models and the reason is very simple: previously theoretical models were to fit experiments with a much lower accuracy than AMS. Now, with our data the models are constantly under evolution, constantly under changes.
I give you a very simple example related to positrons, anti-electrons. The first experiment to observe that the positron rate gradually goes up, with the increase of energy, was HEAT, a balloon experiment. After HEAT, the same trend was observed by AMS-01, our experiment that flew on the space shuttle, and the experiments PAMELA and Fermi. However, now with AMS-02, after ten years of data, we see that the positron rate goes up, up to an energy of 300 billion eV, and after that it drops down. So, it reaches a maximum and then goes down: this is a totally unexpected behavior and there are two possible explanations for this. One is that these positrons come from pulsars (rotating neutron stars with a strong magnetic field), because when a photon interacts with the strong magnetic field of a pulsar, it produces an electron-positron pair. However, at the moment, we are starting to observe that the flux of anti-protons is very much like the positron one and most likely this cannot be explained with pulsars: proton-antiproton pairs cannot be produced in pulsars since the mass of photons is too low to produce the heavy protons and antiprotons.
The second possible explanation is dark matter. There are many dark matter models. If you assume the existence of dark matter particles with a mass of 1TeV, when they collide, they will produce positrons but also antiprotons. And this explanation seems to fit our data. However, this is not yet sufficient: we have to get more data and check whether there is a large number of positrons at higher energies, because a dark matter particle with a mass of 1 TeV would not be able to produce positrons with energies higher that 1 TeV. That's why we continue collecting data above 1 trillion eV and indeed we begin to see the rate of energy goes down at higher energies. It is rather exciting to see this!
Another totally unexpected behavior we observed with AMS-02 is related to the elements across the

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periodic table. In cosmic rays, the elements can be divided into two groups. One group is called “primary cosmic rays”, and these are produced directly from the explosion of stars, and they include hydrogen, carbon, oxygen or iron. Then, there’s a second group, “secondary cosmic rays” (lithium, beryllium, boron and fluorine), and these are the ones produced by the interaction of primary cosmic rays with a medium. We studied the different elements in terms of a property named “rigidity” and we observed that primary and secondary cosmic rays are characterized by different distributions in rigidity. All primary cosmic rays share a similar behavior and can be grouped in two subclasses corresponding to light and heavy elements. Similarly, all secondary cosmic rays have a similar trend in rigidity and can be grouped into two different subclasses. However, just a few weeks ago, we found out there's a third class of cosmic rays, with a rigidity distribution that does not follow neither that of primaries nor of secondaries: these cosmic rays (like nitrogen, sodium, aluminum) are partially of primary and partially of secondary origin. So, we discovered there’s a new class of cosmic rays between primary and secondary not predicted by any theory. Hence, our data based on 175 billion cosmic rays disagree with what hypotized.
One final observation by the AMS experiment I would like to mention is related to the rate of cosmic rays, of radiation. At low energies, well below 100 GeV, the flow of cosmic rays changes violently every day, every month, every year. This observation is of great importance for human journeys to the Moon or to Mars because this radiation could seriously damage astronauts if we do not understand how it works and behaves. Fortunately, AMS will take data until 2028 and so it will go through the 11 years long solar cycle, so eventually we could know whether after 11 years, the rate of radiation will repeat itself or not.

How do you see the future of the AMS experiment? What other results do you expect to achieve?
I think in the next 20 years there will be no other magnetic spectrometer with this precision in space, so it is our obligation to make sure we make no mistakes in the analysis of our data. All the analyses are done by two or three independent international groups. Only if all the groups agree with each other we publish the results.
So far, none of our results agrees with theoretical predictions, so it's difficult to see the future. However, we still need to measure the properties of about 10 elements near iron and above iron, not yet measured, so one aim is to measure all the elements in the periodic table up to the iron region. Another major objective is to measure the positrons and anti-protons rates at very high energies and check if they really fall down very quickly after a certain energy to see whether they really come from dark matter or from something else. Concerning antimatter, we are also beginning to see hints of heavy antimatter, so one of our future goals is to understand how many antiheliums, anticarbons, antioxygens we will see.
Those are fundamental questions; hence, it will take a long time to find the answers.

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Let me add one last thing, for me it has always been a great pleasure to work with Italian and INFN researchers, Italy has always had a good tradition in Physics and I have always enjoyed working with such great collaborators. ■