Hunting Down the Invisible

If cosmologists are correct, there is a form of matter in the universe that is six times more abundant than the matter we know. It is invisible, which is why it’s called dark matter. Postulated for the first time 80 years ago, it has yet to be detected directly. Researchers at the Max Planck Institute for Physics in Munich and the Max Planck Institute for Nuclear Physics in Heidelberg want to solve this cosmic mystery in the next few years.
No other astrophysical topic is causing as much passionate debate among scientists as dark matter. This became particularly clear in the fall of 2011, when physicists from all over the world gathered in Munich to discuss the latest results. Three groups of researchers presented measurement results that were compatible with the detection of the mysterious dark-matter particles – but contradicted each other. Moreover, two further groups hadn’t found anything, and explicitly precluded the positive results.

“It’s possible that the particles have unusual properties, so that they become noticeable in some detectors, but not in others,” says Franz Pröbst, who manages the CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) experiment at the Munich-based Max Planck Institute for Physics. This is one of the detectors that may have detected dark matter.

Manfred Lindner agrees in principle, but thinks it is more plausible that CRESST is seeing a new type of interference effect. Lindner heads the contribution being made by the Max Planck Institute for Nuclear Physics to the international XENON100 experiment, which hasn’t found any events of possible dark-matter particles, even though it has a significantly higher sensitivity.

The heated discussion on “polluted” instruments, sensitivity limits and interference effects is taking place at the highest possible level. CRESST and XENON100 are among the most sensitive and cleanest experiments on Earth. “Our detector is probably the most unpolluted place in the universe,” says Max Planck Director Lindner. In order to understand the demands placed on the technology, a brief look back into history is necessary.

In 1933, the Swiss astronomer Fritz Zwicky, who had immigrated to the US, observed several galaxy clusters. He determined that the individual galaxy systems moved so fast in these clusters that their combined gravity wasn’t sufficient to hold the clusters together. This led him to conclude that there had to be a large quantity of invisible matter that manifested itself only through its gravitational force. Zwicky thus coined the term dark matter.

UNKNOWN PARTICLES CLUSTER TOGETHER TO FORM CLOUDS

But the researcher’s observations were forgotten, and not revived until the 1970s. At that time, astronomers found out that spiral galaxies like our Milky Way rotate so rapidly that they would be torn apart by the centrifugal force if the additional gravitational force of the dark matter didn’t exist.

Today, most astroparticle physicists are convinced that the invisible substance consists of an unknown type of elementary particle. These are thought to have come together to form huge clouds that surround galaxies and are distributed extensively in the galaxy.
clusters. There are a number of further astrophysical indications for their existence, such as the images from gravitational lenses. In addition, widespread opinion holds that the dark matter particles ensure that normal matter was able to condense relatively quickly into stars and galaxies. All pieces of evidence point consistently in the same direction – and without this mysterious agent, which also acts as a glue, we wouldn’t exist at all.

Several properties of the invisible particles can be derived from past observations and theoretical arguments. These predict that the most plausible candidates have a mass that corresponds approximately to the mass of atoms. They are electrically neutral and have virtually no interaction with...
normal matter. In other words, they pass almost unhindered through all bodies in the universe. These properties earned them the name “weakly interacting massive particles,” or, characteristically, WIMPs.

WIMPS PASS THROUGH OUR BODIES

Summarizing everything that is presumed to be known today, around 100,000 of these particles race through an area the size of a thumbnail every second on Earth – they even race through our bodies without us noticing it in the slightest. This sounds like fantasy, but it really isn’t that unusual. During the same period of time, around 65 billion neutrinos, which originate in the interior of the Sun, pass through the same area; and it is already possible to make these ghost particles visible through rare collisions with matter.

All experiments that are currently in progress assume that the dark matter particles are also quite capable of colliding with normal atoms, albeit with extremely low frequency. But this ought to give them away. The unequivocal discovery of WIMPs would be a sensational confirmation of the new world view, and would probably be honored with a Nobel Prize.

The recipe is similar for all measuring instruments: take a suitable detector material and wait for the very rare case that a WIMP collides inside with an atomic nucleus – and generates a brief flash of light. Electrons will be released, too, because the atom that gets hit will collide with further atoms and the outer electrons can separate from the atom.

If the material is a crystal, the collision energy is then transferred to the crystal lattice, and the detector heats up. There are therefore three measurands: light, free charges and temperature. However, none of the current detectors can measure all three of them simultaneously, but rather only ever two at a time. This has implications for the current discussion of the findings.

Franz Pröbst has spent the last 15 years working on the CRESST experiment, which also involves physicists from the TU Munich, Tübingen and Oxford. At the heart of the apparatus are crystals of calcium tungstate, each

Tunnel of enlightenment: The CRESST experimental module is in the Gran Sasso underground laboratory, where 1,400 meters of Abruzzi rock shield it from cosmic radiation. The researchers must also protect their sensitive apparatus from further interfering influences. Radioactive trace elements in the rock, in particular, cause undesired signals. The most harmful source of interference is radon 222, which is produced in the natural decay of uranium and thorium.
having a height and diameter of four centimeters. Although several million WIMPs should pass through one of these detectors every second, Pröbst doesn’t expect more than one collision per month. Such an event releases a very weak flash of light, and the crystal heats up by a few millionths of a degree. How can this be measured?

SENSITIVE EXPERIMENTS AT ABSOLUTE ZERO

“Back when we started with the experiment, there was no technology for measuring this,” remembers Pröbst. The physicist, together with Wolfgang Seidel and Leo Stodolsky, developed the cryodetectors used today. They were given this name because they operate at an extremely low temperature of around one hundredth of a degree above absolute zero (minus 273.15 degrees Celsius). A thin tungsten film is applied to one side of the crystal and serves as a sensitive thermometer. The temperature is accurately adjusted so that the film is in a transition state between normal conductivity and superconductivity. Even the slightest heating increases the electrical resistance so much that it can be measured.

This can be visualized as a sensitive seesaw that is just balanced. Even the smallest weight can make one side move down. Maintaining the temperature stabilization to within a millionth of a degree presents a huge challenge. Each tungsten film has its own transition temperature that must be adjusted individually. “We spend months calibrating the experiment,” reports Pröbst’s colleague Michael Kiefer from his own painful experience.

With CRESST, the physicists can also detect the flash of light that a WIMP is thought to generate as it collides with an atom in the crystal. They do this with mirrors that completely surround the crystal and deflect the light to a further low-temperature sensor. This heats up, enabling the researchers to ultimately deduce the light energy.

It took many years of work to get these detectors to function. However, there is a further problem: nature has many other sources up its sleeve that generate signals similar to those generated by the WIMPs in the crystals. A first step was the installation of CRESST in the Gran Sasso underground laboratory. Underneath 1,400 meters of rock in Abruzzi, the experiment is largely shielded from the particles of cosmic radiation that incessantly pelt down into the Earth’s atmosphere from space.

The worst enemy, however, is natural radioactivity in the form of very minute traces of unstable isotopes. The radioactive radon isotopes, for example, that are present everywhere as a
consequence of the decay of uranium – even in the ambient air of a normal house – have an interference effect. The atomic nuclei, electrons, neutrons and gamma rays released in radioactive decays can penetrate into the detector and cause a signal similar to that generated by a WIMP.

**A 44-TON SHELL REDUCES THE INTERFERENCE EFFECTS**

In order to protect the crystal detectors against stray radiation from radioactive decays, they are manufactured from high-purity materials. And they are surrounded by several shells made of polyethylene, lead and copper and weighing a total of 44 tons. Nevertheless, a small dirt effect remains. “We are now measuring an event only approximately every one hundred seconds,” says Kiefer. These events are the background interference.

The situation isn’t without hope, however, because the interference effects can be distinguished from the expected WIMP signals by analyzing the light energy and the heating of the crystal. At the end of 2011 in Munich, the CRESST group presented what is still a valid result of a series of measurements taken from May 2009 to April 2011. The researchers recorded 67 events in total, of which they could explain only 46 with known interference effects. So do the remaining 21 originate from WIMPs?

If this is the case, then the particles have a mass that roughly corresponds to the mass of a carbon atom. The probability that this is a random, statistical variation is 1 in 100,000. “But it could still be an unknown background interference,” says Pröbst. The aim is currently to reduce this background to one tenth with the aid of further screening measures. In addition, the researchers are doubling the number of crystals to 18.

The experiment is now being set up in the Gran Sasso laboratory and is set to start up again in early 2013. If the protective measures have an effect, a further two years of data acquisition should make it clear whether CRESST really has detected WIMPs or not. The race to discover dark matter, which involves a dozen or so groups around the world, is therefore in full swing. For the first time, a solution to the mystery seems within easy reach. But at the moment, the results are still contradictory.

Two groups in the US and Italy have also announced a positive result – albeit in a different mass range than that at CRESST. They are all contradicted by the XENON100 experiment that is likewise running in the Gran Sasso laboratory, and an American experi-
XENON100 uses 162 kilograms of liquid xenon as the detector material. If a WIMP collides with an atom in the detector, it generates a flash of light that is recorded by sensitive photodetectors. Furthermore, electrons are released and then pulled to the surface by an externally applied electric field, where they are measured.

ONE KRYPTON ATOM AMONG A TRILLION XENON ATOMS

In this experiment, too, the worst enemy is stray radiation from radioactive decays, especially from radon and krypton. The researchers procure their xenon in as pure a form as possible from the few producers in the world. They then invest a lot of time and effort in further purifying the substance. “The fluid contains as few impurities as a cubic kilometer of pure water into which somebody has coughed once,” is how Manfred Lindner exemplifies the situation.

The Heidelberg-based Max Planck Institute for Nuclear Physics contributes its decades of experience in neutrino research to this cooperation. In its day, the solar neutrino experiment GALLEX aimed to detect a very small number of germanium atoms that were produced by neutrinos in a large quantity of gallium. “Today we can detect one krypton atom among more than a trillion xenon atoms,” says Hardy Simgen, who knows the presumably most sensitive apparatus in the world for gas analysis inside out. “On average, there are 8,500 radioactive decays per second in the human body. We detect a few decays per year in 100 kilograms of material.”

All materials that are used for the experiment first pass through this apparatus. Recently, there was a problem...
with new light sensors for the follow-up project with one ton of xenon. Given the enormous purity requirements, they were too radioactive, and would thus destroy the measurement completely. The physicists have now teamed up with the manufacturer to select purer materials in order to meet the requirements.

The xenon is in a continuous purification cycle – a type of dialysis that continuously removes the radon that incessantly finds its way into the detector. This is where the researchers in Heidelberg are contributing their considerable experience from the solar neutrino experiment. They are using a mobile radon extraction unit to test the purification efficiency under realistic conditions.

And the scientists successfully employed a trick to make XENON100 currently the most sensitive of all WIMP experiments by far: since the impurities penetrate into the xenon from the exterior walls, the physicists select only those events that occur in the inner region of the detector. They therefore use only the central, particularly clean third of the total volume for the WIMP search.

It has thus been possible to reduce the number of interfering events to a minimum. This is why their result – namely no significant WIMP event – is very convincing. If CRESST really had detected dark matter particles, XENON100 would have had to register more than one hundred events.

Manfred Lindner draws the following conclusion from the current situation: One solution would be that two of the three experiments measure an unintelligible background, while the other one really sees WIMPs. However, these would then have to possess very unusual properties in order to remain invisible to XENON100. This can’t be completely excluded, though, because CRESST, for example, measures the flash of light and the heat that a WIMP generates in the detector when it collides with an atom. XENON100, in contrast, measures the flash of light and the ionization rate generated. “The other solution, with less specific assumptions, is that none of the signals seen so far originates from WIMPs,” says Lindner.

**DOUBTS ABOUT THE VALIDITY OF THE LAW OF GRAVITATION?**

The development continues at the XENON experiment. Preparations are underway to expand it to one ton of xenon. The larger the detector, the more WIMP events can take place in it. However, the problem of the pollution over the larger surface also increases, and so do the demands being placed on the purity of the detector materials and the xenon. This is where the purists from Heidelberg can bring the full scope of their know-how to bear. In late 2014, the apparatus is to start up with a sensitivity increased by a further factor of one hundred and provide a first result in 2016.

If the dark particles remain unseen, things will become very tight for the most plausible explanation of dark matter in the form of WIMPs. Researchers would then have to consider other particles more seriously. If dark matter doesn’t exist after all, doubts could be expressed about the validity of the laws of gravitation. There have long been alternative explanations, but they can’t provide a uniform, consistent explanation for all the astrophysical phenomena for which dark matter is postulated. Moreover, it would then be necessary to modify Einstein’s theory of gravitation in a way that, to phrase it carefully, would seem to have very little basis.

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**TO THE POINT**

- Around 23 percent of all matter present in the universe remains hidden from astronomical instruments.
- Even as early as the 1930s, observations of galaxy clusters led Fritz Zwicky to conclude that dark matter existed.
- Today, physicists around the world are employing special detectors to search for this mysterious substance, which should manifest itself in so-called WIMPs.
- Since the WIMPs hardly interact at all with normal matter, it is extremely difficult to detect them. The measurement results to date contradict each other to some extent and are the subject of heated debate.

**GLOSSARY**

**Galaxy cluster:** Conglomerations of up to several thousand galaxy systems that are bound to each other by gravity.

**Gran Sasso laboratory:** The Gran Sasso tunnel passes through the massif of the Gran Sasso d’Italia in Abruzzi, Italy. Not only is it the longest double-tube highway tunnel in Europe, but auxiliary installations also accommodate the Laboratori Nazionali del Gran Sasso, the world’s largest underground experimental laboratories for elementary particle physics.

**Gravitational lens:** The phenomenon predicted by Einstein where light is diffracted by the gravitational field of a mass in the same way it is diffracted by an optical lens. In space, this effect is usually caused by a galaxy or a galaxy cluster.

**Neutrinos:** Electrically neutral particles with minuscule mass. In the standard model of elementary particle physics, there are three species: the electron neutrino, the muon neutrino and the tau neutrino. Neutrinos hardly interact at all with matter; they thus pass almost unhindered through even large layer thicknesses – the entire Earth, for example.