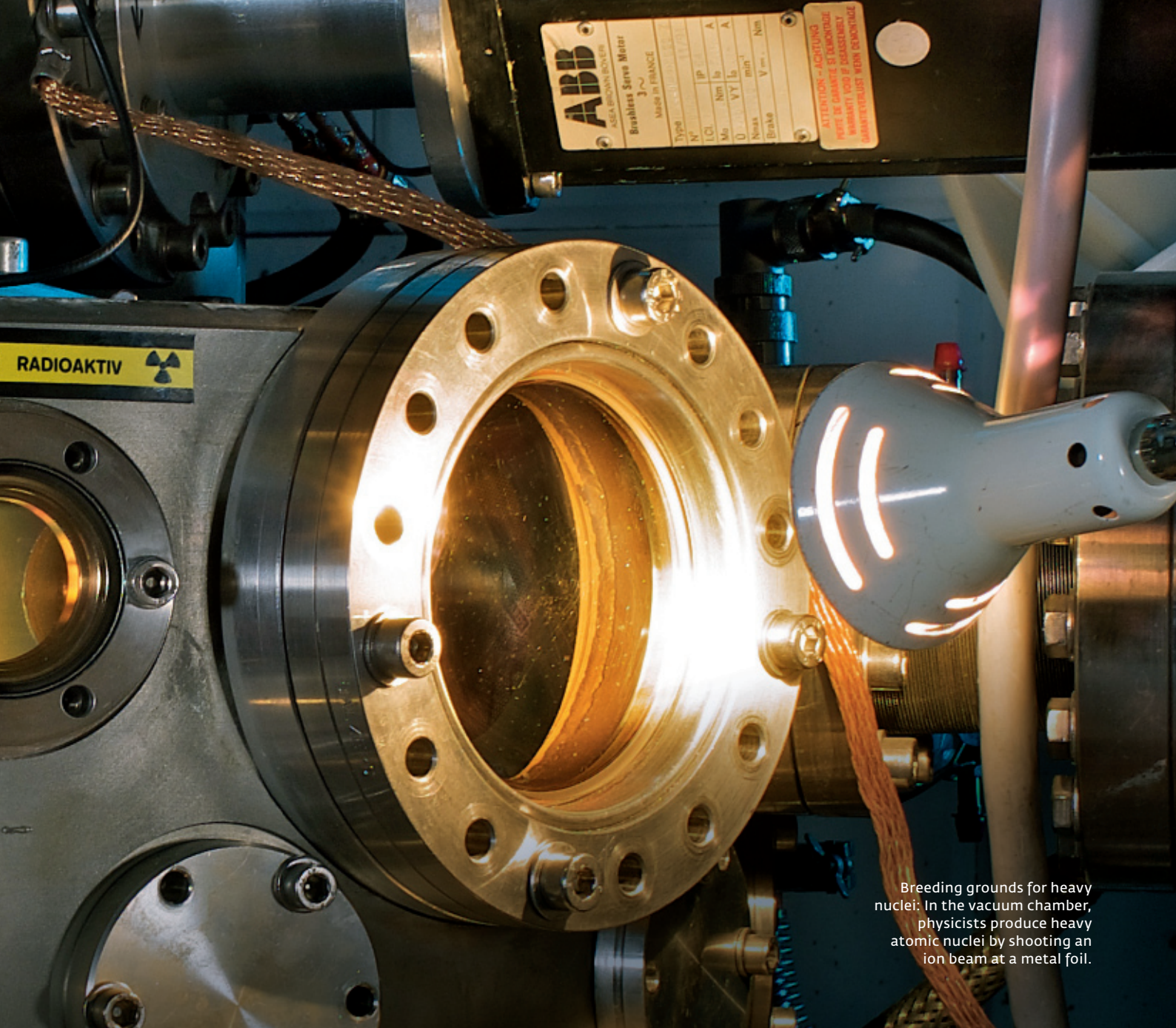


Physics in the **Balance**

Klaus Blaum, Director at the **Max Planck Institute for Nuclear Physics** in Heidelberg, and his colleagues use clever tricks to weigh atomic nuclei to answer key questions in the field of physics – questions like how stars breed chemical elements. Or what makes up the dark matter that holds the universe together.



Breeding grounds for heavy nuclei: In the vacuum chamber, physicists produce heavy atomic nuclei by shooting an ion beam at a metal foil.

TEXT **ROLAND WENGENMAYR**

Weighing atomic nuclei – why undertake such a task? Klaus Blaum is obviously used to such questions. The young Director at the Max Planck Institute for Nuclear Physics in Heidelberg patiently explains why he is constructing what is probably the most sensitive balance to date for tiny objects. Close to 40 group members are working on these precision experiments in collaboration with partners from other scientific institutions. The conversation quickly turns into a journey of adventure from tiny atomic nuclei to the great questions in physics. It is amazing what insights the weighing of atomic nuclei can provide.

Time and again, Blaum jumps up and goes over to the large chart of nuclides on the office wall: a broad panorama of the diverse atomic nuclei with their physical properties. Blaum moves his finger over small squares that symbolize the chemical elements and their lighter or heavier isotopes with their varying numbers of neutrons; the heavier an element, the further to the right its position on the chart. To the extreme right, beyond uranium – the element with the atomic number 92 – for example is where the realm of the heavy and superheavy elements begins. These artificially produced nuclei do not remain stable – they decay after a few millionths of a second or a few seconds at most. >

- 1 Tiny object, big balance: Klaus Blaum stands in front of Shiptrap – the apparatus he and his colleagues use to determine the mass of heavy atomic nuclei.
- 2 The source for heavy atomic nuclei: In the foreground on the left is the vacuum chamber where the nuclei are produced. In the grey box to the right of the chamber is a cooling unit; in the background (illuminated in blue) is the equipment that guides an ion beam into the vacuum chamber. The nuclei are weighed in Shiptrap (top image).

The physicists have already reached element 118, but the International Union of Pure and Applied Chemistry (IUPAC) has officially confirmed only the elements up to 112. Beyond these elements, the chart ventures into unknown territory. Physicists have long assumed there is an island of stability somewhere near element 120. “The nuclei there could live for years,” explains Blaum. Subtle quantum effects are assumed to form the stabilizing nuclear glue on this island, which also exerts a powerful force of attraction on the Max Planck researcher. He is not interested in holding weight records in physics, but in how atoms – the building blocks of matter – are formed.

“The exciting question for me is how the world came into being,” says Blaum, and promptly arrives at astrophysics because, after all, stars breed almost all the atomic building blocks of matter beyond hydrogen and helium. The scientist is particularly fascinated by the nucleosynthesis of heavy chemical elements. These are produced only under the extreme conditions that exist during a particularly dramatic death of a star – a supernova.

NUCLEI FUSE ONLY DURING HEAD-ON COLLISIONS

Astrophysics has even more problems in store, and Klaus Blaum wants to come closer to solving them by weighing atomic nuclei. The fundamental question concerns the mass of the neutrinos – the omnipresent, all-penetrating ghost particles of physics. The answer would, among other things, add a further, important piece to the jigsaw puzzle of the unsolved mystery surrounding dark matter in the universe. Like any cleverly thought out precision experiment, a balance for atomic nuclei is thus simultaneously useful in several basic research fields. But what does such an extreme

balance look like? And how does it work? Blaum wants to demonstrate just this at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt/Germany.

Two days later, we are standing inside a large experimentation hall in Darmstadt in front of Shiptrap. This seemingly chaotic jumble of tubes, cables and bright digital displays looks nothing like a scale, although in reality it has been thought through in great detail. Atomic nuclei are weighed in a completely different way than flour or people, of course. Dr. Michael Block provides a tour through the facility. The atomic physicist is the project leader of this experiment at the GSI, which is a collaborative effort between the Max Planck scientists from Heidelberg and other German and international research groups.

Block starts by pointing out where the heavy nuclei are created. This is where the Darmstadt physicists were the first to produce a total of six super-heavy elements, including numbers 110 and 112, which they were then allowed to name darmstadtium and copernicium. The crucial element can be found in a vacuum chamber whose reinforced windows are reminiscent of an old-fashioned diver’s helmet. A metal foil clamped in a revolvable wheel gleams behind the window. “This is the target,” explains Block. A beam of ions, electrically charged atoms such as calcium ions, for example, strikes this target. Before impact, the electromagnetic fields of the GSI’s powerful accelerator have boosted their speed to tens of thousands of kilometers per second.

One of the many trillions of ions in the beam sometimes lands a direct hit: its atomic nucleus collides head on with the nucleus of an atom in the metal foil. This is an extremely rare event, however, as atomic nuclei are unimaginably tiny. Their diameter amounts to only a few femtometers: a few mil-

lionths of a millionth of a millimeter. If a nucleus from the ion beam collides head on with a nucleus in the foil, they fuse together. This results in a heavy or even superheavy atom – albeit one that is also electrically charged.

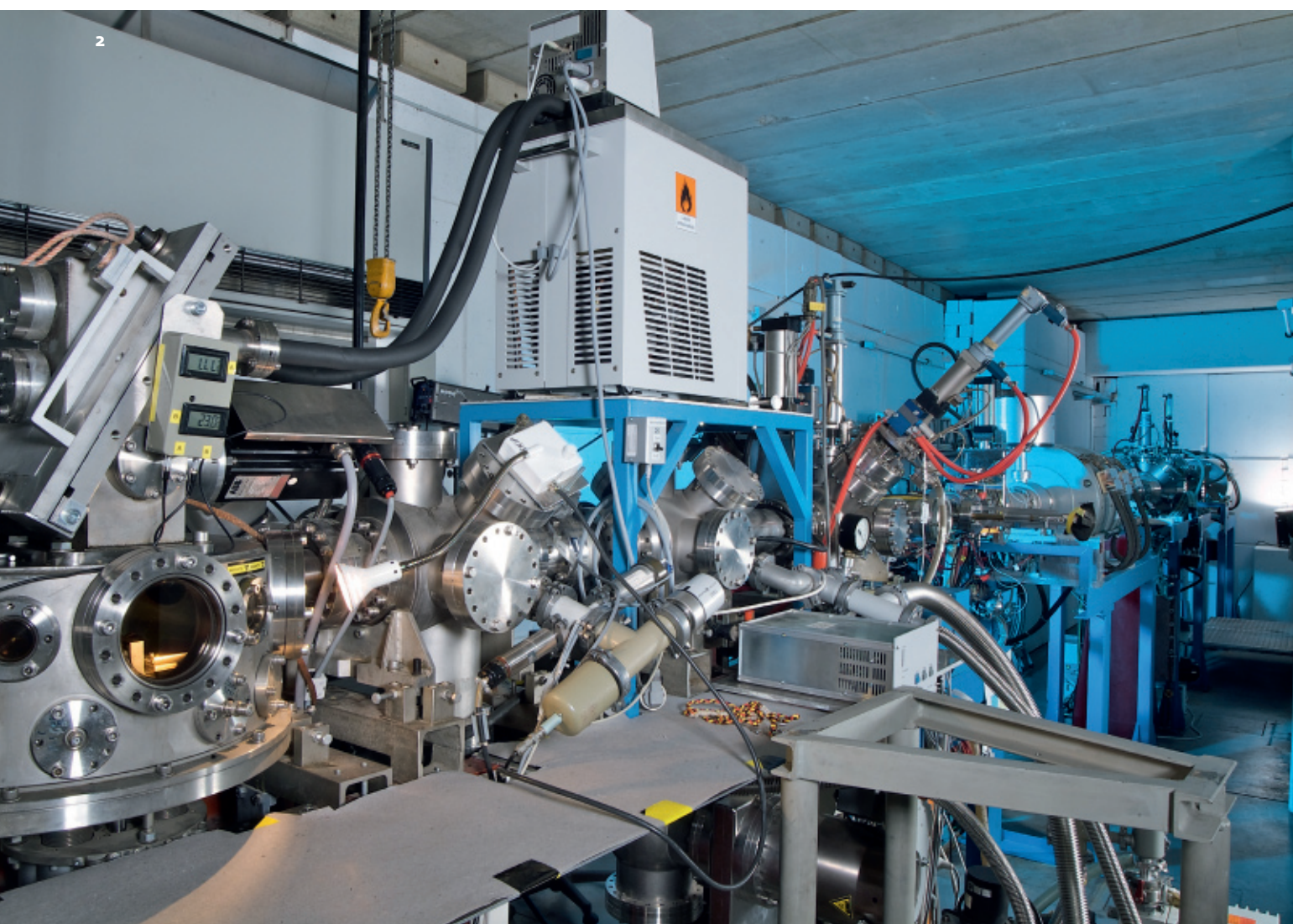
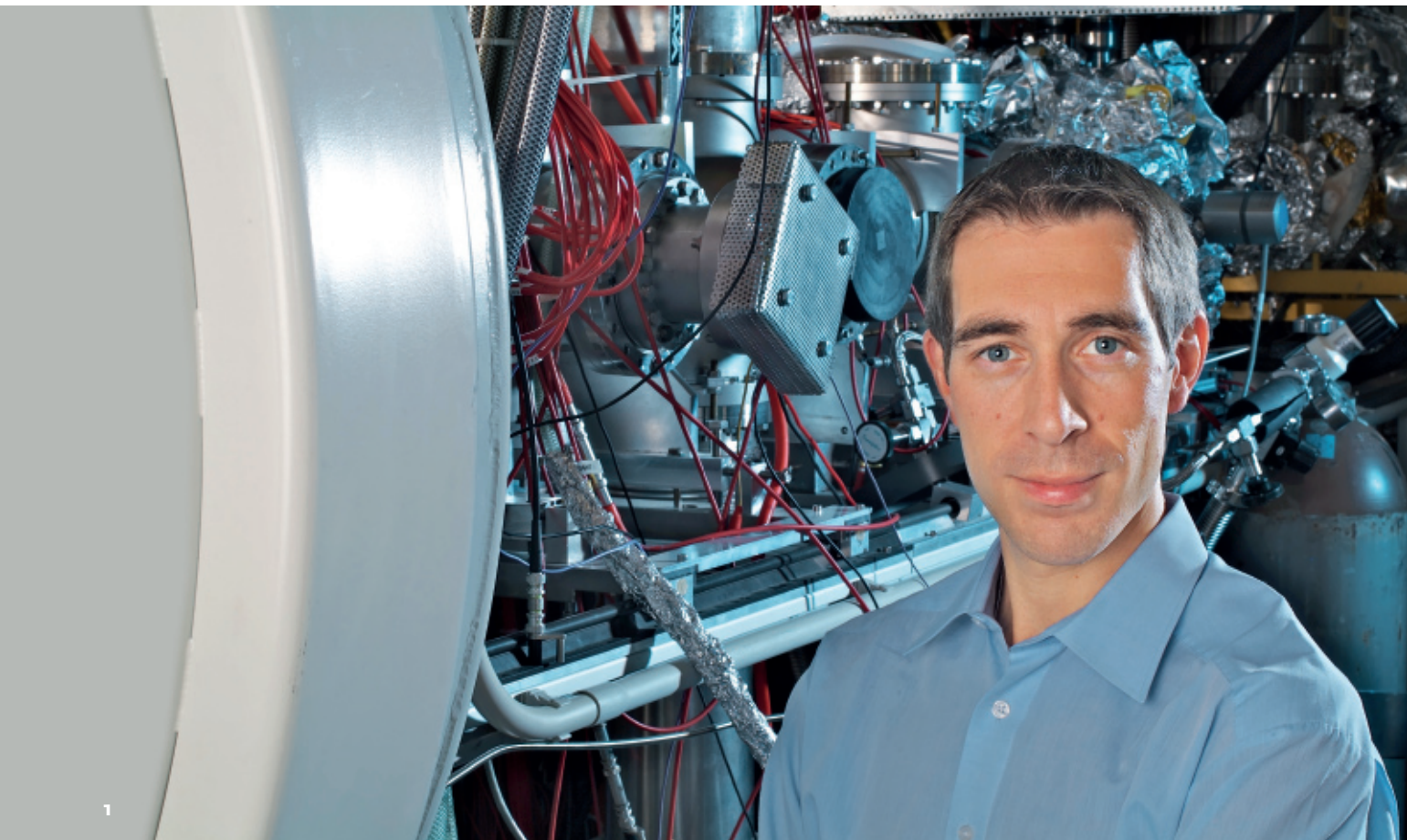
The momentum tears the heavy ion out of the back of the metal foil. With Ship (Separator for Heavy Ion reaction Products), it initially passes a velocity filter that separates it from the beam particles. The ion then arrives at Shiptrap. Before the actual weighing can begin, it must first be slowed down from its high velocity to almost zero – and this happens over a distance of less than half a meter!

THE ATOM MEANDERS ABOUT IN THE TRAP

Another foil and an elongated cell filled with gaseous helium act as the decelerator: in the cell, the heavy ion collides with a cascade of helium atoms in a massive pile-up. Although the braking principle is simple, years of research have gone into developing the gas cell. Even with the technology used today, only a small percent of the heavy ions survive the deceleration process; most of them remain stuck in the foil or hit the cell wall, where they decay.

The ions that survive then arrive at the trap part of the Shiptrap. The name of the scale was actually chosen because it consists of a so-called Penning trap, named after the Dutch physicist Frans Michel Penning. It is positioned in a very strong superconducting magnet, and its magnetic field and the trap’s electric field together form a cage for the electrically charged ion. In the cage, the particle meanders about in an orbit resembling a spiral bolted together to form a circle.

“An ion circles a million times per second on this rosette-shaped orbit, for example,” explains Blaum. This circu-



lation frequency already contains the precise information on the weight or, to use the more precise physical term, the mass of the ion. There is, unfortunately, no simple way of just taking a reading. What is required is a trick that Blaum illustrates with an example: imagine that the ion oscillates to and fro on its orbit, as if on a swing. The particle is excited by an electromagnetic RF signal. The more accurately its adjustable frequency corresponds to the characteristic frequency of the ion in the

trap, the faster the ion builds up its speed. Finally, it is ejected from the trap and ends up in a detector. The time it takes the ion to fly there tells the physicists the characteristic frequency and thus the mass of the ion. The researchers can ultimately use this to calculate the mass of the atomic nucleus with high precision.

Using this method, Blaum, Block and their partners recently succeeded in determining the mass of the atomic nucleus of nobelium, the element 102,

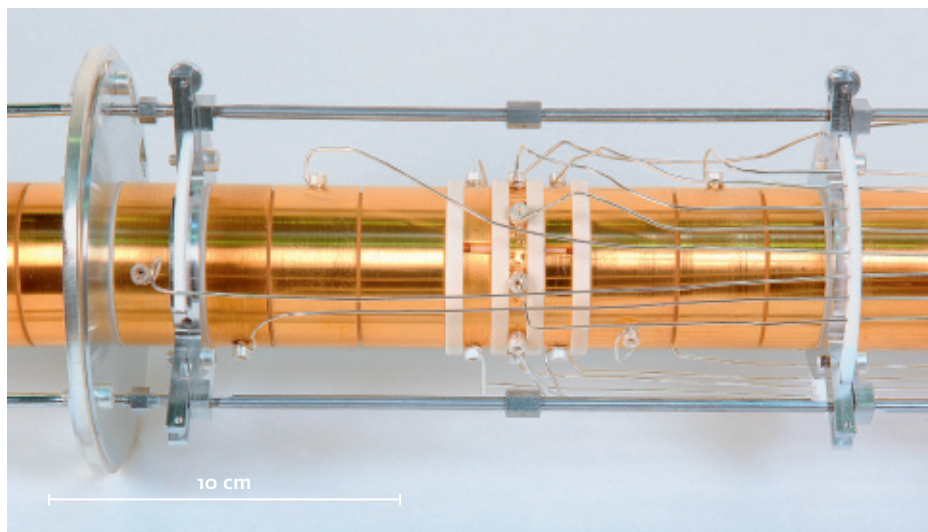
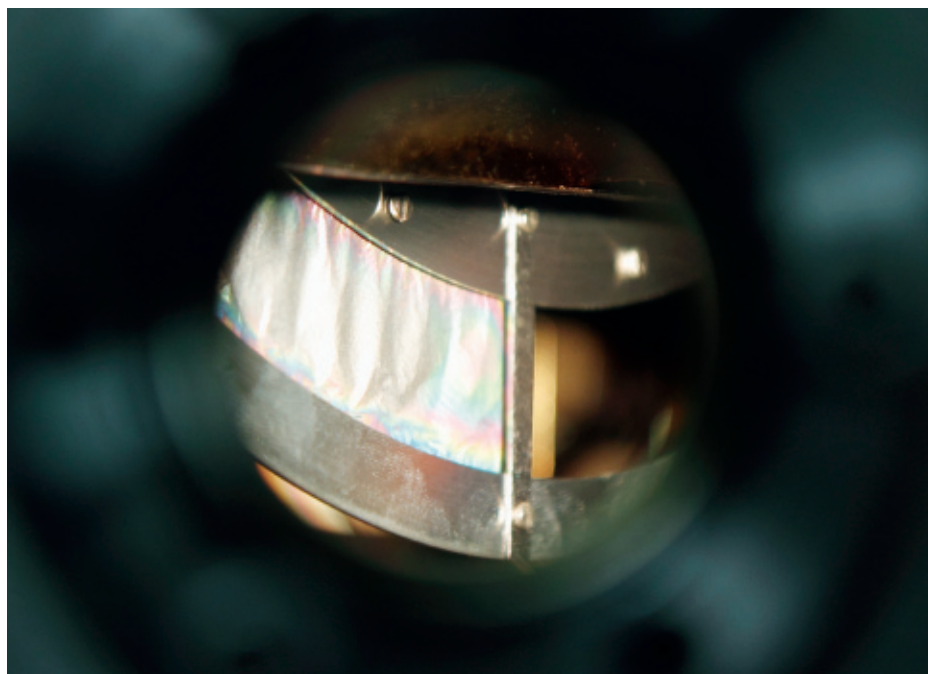
with very high precision. “Our publication in the journal *NATURE* caused quite a stir in the press,” says Klaus Blaum with pride. “In Spain, even *EL PAÍS* carried the report of one of our Spanish group leaders on the front page,” recounts Michael Block.

The present measuring procedure has the disadvantage that each measurement destroys the valuable ion. Even in the case of nobelium, only very few ions per hour ended up in the trap on average. And in top accelerators, such as the one at the GSI, the even heavier nuclei are sometimes produced only once per day or per week. But the physicists need around 100 ions per mass measurement. This is a problem, because measurement campaigns lasting 100 weeks would be much too expensive at this very popular research facility.

Blaum and his team are thus now working on a particularly sensitive detection technology that does not destroy the ion, and makes it possible to conduct a mass measurement on a single ion. The trick is that the ion’s positive charge attracts negatively charged electrons in the trap wall. These circulate as a tiny mirror current in time with the ion. The researchers can measure the current – albeit only with extremely sensitive instruments. This new technology now makes it possible to weigh single atoms with a very high degree of precision.

THE MODELS OF THE ATOMIC NUCLEI ARE IMPRECISE

Klaus Blaum is developing the method with colleagues at the Max Planck Institute for Nuclear Physics and the University of Mainz. “The ion must survive in the trap for at least a few seconds if it is to be of use,” says the researcher. The method is therefore not suitable for ions that decay quickly. However, if superheavy nuclei that are long-lived or



top: A glimpse into the inner sanctum: If a nucleus of one of the ions in the beam collides head on with an atomic nucleus in this metal foil, a heavier nucleus is produced and ejected away.

bottom: Penning trap that serves as the scale for the heavy nuclei.



Michael Block checks the electrode voltages on the trap for the heavy nuclei. A superconducting magnet in the white drum generates the likewise required magnetic field.

even stable again really do exist, then this balance would be the detection method of choice for new elements.

The current standard method can detect only ions that quickly decay again. It has been used for decades at all particle accelerators that produce heavy elements. Their detectors react only to the decay products, from whose data the physicists can reconstruct the original nucleus. The nuclear mass can also be derived from this, but this can lead to errors. One reason is that the nuclear fragments can surreptitiously carry with them a portion of the energy that is released in the decay – precisely what happens when protons and neutrons in the nucleus jump to higher quantum states, similar to the electrons in the atomic shell.

The nuclei absorb excitation energy in the quantum jump, although this energy remains virtually invisible to the standard method. This causes a certain error when the nuclear physicists calculate the mass of the decayed heavy nucleus from the decay products detected, as energy and mass are equivalent – that is, two sides of the same physical coin.

Albert Einstein recognized this back in 1905 and expressed this fact in his famous equation $E = mc^2$.

The theory is still a challenge in modern nuclear physics. Although physicists can now calculate the behavior of the electrons in the shells of atoms and molecules quite accurately, they still have difficulties with the protons and neutrons in the tiny nuclei. Their theoretical models on the structure and internal cohesion of the nuclei are significantly less accurate than the precision that can now be achieved in experiments. This is because the nuclear building blocks form a system comprising many particles. Unfortunately, there is no exact mathematical solution for such systems with more than two particles. Theoretical physics must thus find clever approximative solutions.

NUCLEI WITH FILLED SHELLS MIGHT REMAIN STABLE

This presents a special challenge in relation to the complex nuclei. With the exception of simple hydrogen, the electrons in atoms also form many-particle

systems; however, they are better behaved, as only the electromagnetic force binds the negatively charged electrons to the positive nucleus. This is the second strongest of the four known fundamental forces in physics. It is also effective in atomic nuclei, but in a destructive way, forcefully driving the identically charged protons apart.

The existence of our material world is owed to a further force that comes into play in the nucleus, but that also makes it more complex. This strong force forces the protons and neutrons together, but it has only an extremely short range. In very large nuclei, the weaker but longer-range electromagnetic force thus gains the upper hand and causes them to decay.

This can be prevented by a stabilizing effect from quantum mechanics. It also plays an important role in the shell of electrons around the atoms. Electrons, protons and neutrons belong to a type of quantum particles that are extreme individualists: each one of them claims one quantum state for itself. However, there is only a strictly limited number of these quantum positions

in both the electron shell and the nucleus. They form shells, similar to rows of seats in the theater.

In the electron shells, a full row of electron seats gives the noble gases their properties. The filled shells have very low energy and are thus very stable. Nuclear physics expects the same for atomic nuclei with their shell-like structure: each stable shell that is completely filled with protons or neutrons corresponds to a magic number of nuclear building blocks.

It is thought that this magical quantum property will glue together even superheavy nuclei, which should actually explode. Blaum points to the chart of nuclides and to the mass region around 120 protons and 184 neutrons: "Do such magical shells also exist there?" If the answer is yes, then this is probably the location of the island of stability – if it exists at all.

Thus far, however, the physicists have not succeeded in producing such superheavy nuclei with large numbers of neutrons. It therefore remains to be seen whether the models of nuclear physics apply to predictions of this type at all. Highly accurate weighing of slightly lighter nuclei can reveal which of the competing nuclear models best describes nature. It should then be possible to determine in more detail whether the hypothetical island of stability exists and, if it does, where it is.

The stability of nuclei has already led Blaum to the novae and supernovae in a long-standing cooperation at the CERN European Research Laboratory in Geneva. These stellar events are assumed to be the breeding grounds for the heavier elements. Although, in contrast to the GSI, the Isolde facility there can produce only lighter atomic nuclei, some of them play a decisive role during the stellar death throes.

BREEDING PROCESSES IN STARS MAKE GOLD VALUABLE

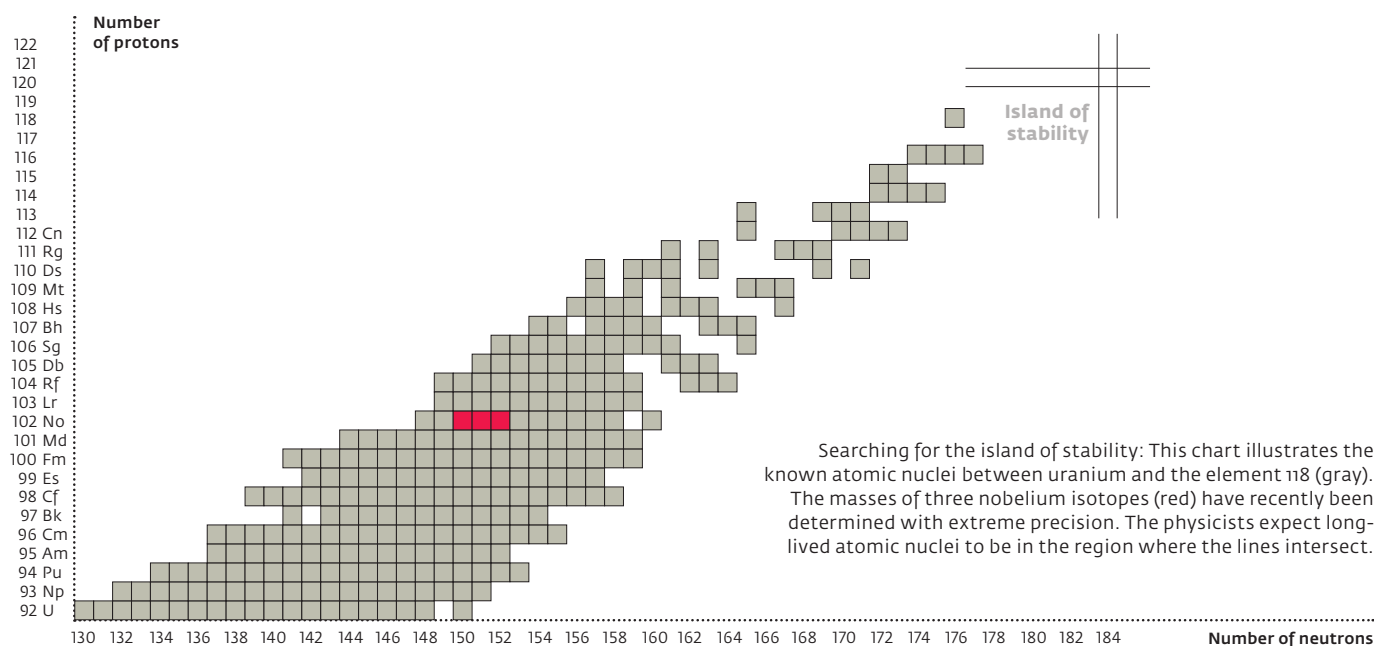
These so-called waiting point nuclei act like stop signals on the way to even heavier elements. In supernovae, this path is provided by a process to which around half of the elements beyond iron in the chart of nuclides owe their existence. It involves a nucleus capturing one of the neutrons that race through the dying stars in enormous quantities. A radioactive decay, so-called beta decay, then converts a neutron in the nucleus into a proton, thereby releasing an electron. The new proton increases the atomic number by one and the new nuclide moves one place to the left and up in the chart of nuclides.

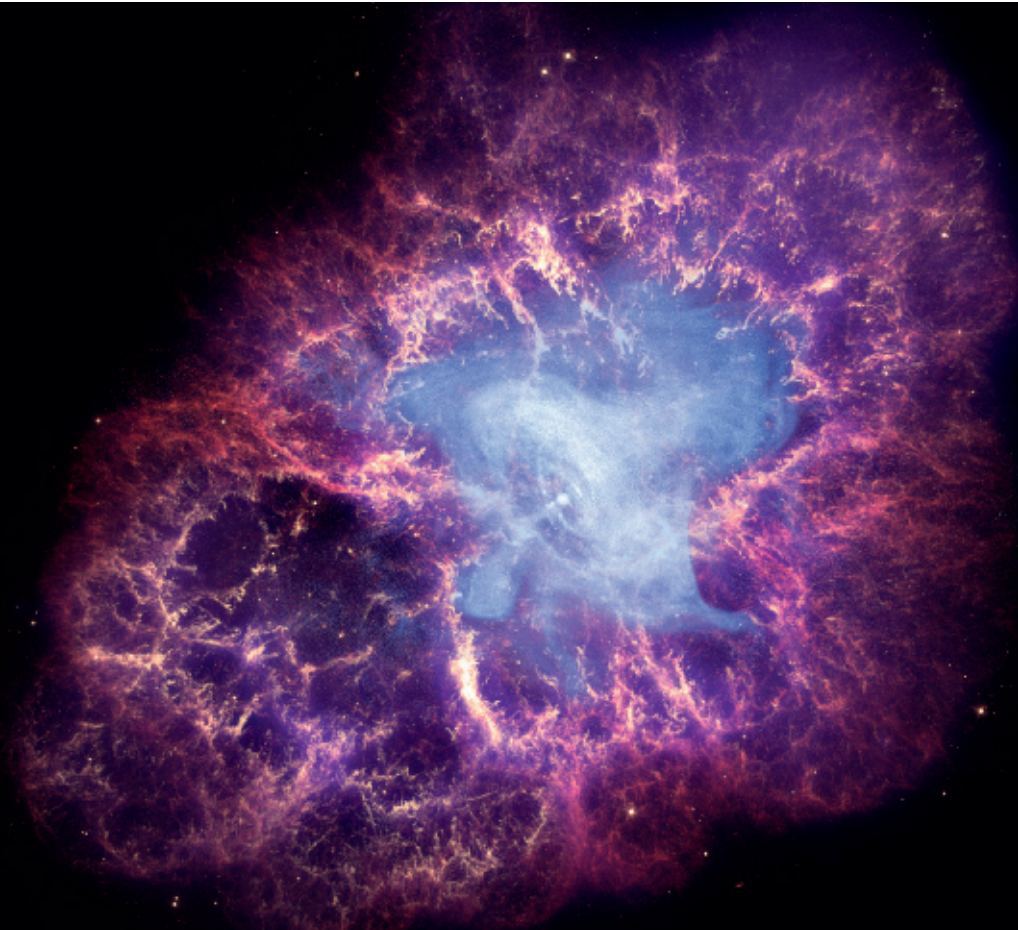
The waiting point nuclei can be imagined as gluttons that have eaten their fill standing in front of a buffet that is heavily laden with tasty neutrons. They

have the choice – either swallow another neutron and become even heavier, or explode. Since the waiting point nuclei find it difficult to choose between the two, the formation of even heavier elements must wait for a while – which can significantly delay the breeding process. "We now understand why so little gold is formed, for example, and is thus so valuable," explains Blaum.

Although current nuclear models allow one to guess which atomic nuclei act as waiting point nuclei, only the precise mass measurements of Blaum and his colleagues provide accurate information on the candidates' shell structure. They recently used the Isoltrap balance at CERN, which operates according to the same principle as Shiptrap, to successfully prove that a stable shell of 50 protons and 82 neutrons in the very heavy nucleus of the tin-132 isotope (tin is element 50) plays such a prominent role in supernovae.

Klaus Blaum is also interested in the "flyweight class" of the particles. Together with physicists from the Karlsruhe Institute of Technology, the Heidelberg-based scientists are on the trail of the neutrino masses. In addition, there is the Karlsruhe Tritium Neutrino experiment "Katrin" whose task is to measure a specific radioactive decay with extreme accuracy: the beta decay of the heavy hydrogen isotope tritium.





A source of heavy elements: The crab nebula is proof of a supernova. The heaviest natural elements are produced in such stellar explosions.

During this process, the tritium nucleus with its proton and two neutrons decays into a helium-3 nucleus; this consists of two protons and one neutron. Consequently, one of the neutrons has transformed into a proton in a beta decay. This is caused by the weak force, the third fundamental force in physics. In order for the balance of the electric charges to be correct, the electrically neutral neutron must produce a negative electron in addition to the positively charged proton. However, there is another gap in the balance sheet of a second physical property: the total angular momentum (spin) before and after the decay. This deficit is balanced by an electron antineutrino that is released as a further particle. Its mass is what the physicists are aiming for.

To this end, “Katrin” records with a high degree of accuracy how much energy the electrons released in the decays carry away with them. “We, on the other hand, want to use a device in Heidelberg to measure the difference in energy between the tritium and the helium,” explains Blaum. Since, according to Einstein, energy is

equivalent to mass, it must be possible to calculate the neutrino mass from the two measured values. The Heidelberg scientists are thus building a particularly precise scale that will measure to within one million millionth of the nuclear mass.

This research project could cause a sensation. Although the Standard Model of particle physics, a mainstay of modern physics, allocates zero mass to the neutrinos, it is now clear that they must have a mass. However, the question as to how heavy the different types of neutrinos are remains unanswered. If the Karlsruhe Katrin researchers, together with the Heidelberg Max Planck physicists, succeed in weighing one type of neutrino, this would have far-reaching consequences. For the first time, it would be possible to estimate whether and to what extent these ghost particles contribute to the mysterious dark matter in the universe.

The precision balance for atomic nuclei thus helps answer key physics-related questions. No wonder, then, that Klaus Blaum summarizes as follows: “I believe that the new methods have led to a renaissance of nuclear physics.” ◀

GLOSSARY

Neutrinos

Electrically neutral elementary particles with very low mass. Physicists distinguish between electron neutrino, muon neutrino and tau neutrino, each of which exists as a counterpart to electrically charged particles (electron, muon, tau particle). Neutrinos interact very little with matter and therefore also penetrate the Earth practically unhindered. They are produced in radioactive beta decay and nuclear fusion processes in stars, for example. Just as antiparticles exist for other building blocks of matter, there are also antineutrinos.

Characteristic frequency

Every object that can oscillate has at least one characteristic frequency – no matter whether it is an electron, pendulum, violin string, suspension bridge or skyscraper. If it is pushed or excited with this frequency, it oscillates with particular strength.

Standard Model of particle physics

This describes the elementary particles and the interactions between them, but includes only three of the four fundamental forces; gravitation is not taken into account. It also assigns a rest mass of zero to the neutrino, a fact that has since been proven to be incorrect. Physicists are thus trying to expand the model – one of the large unsolved problems in physics.