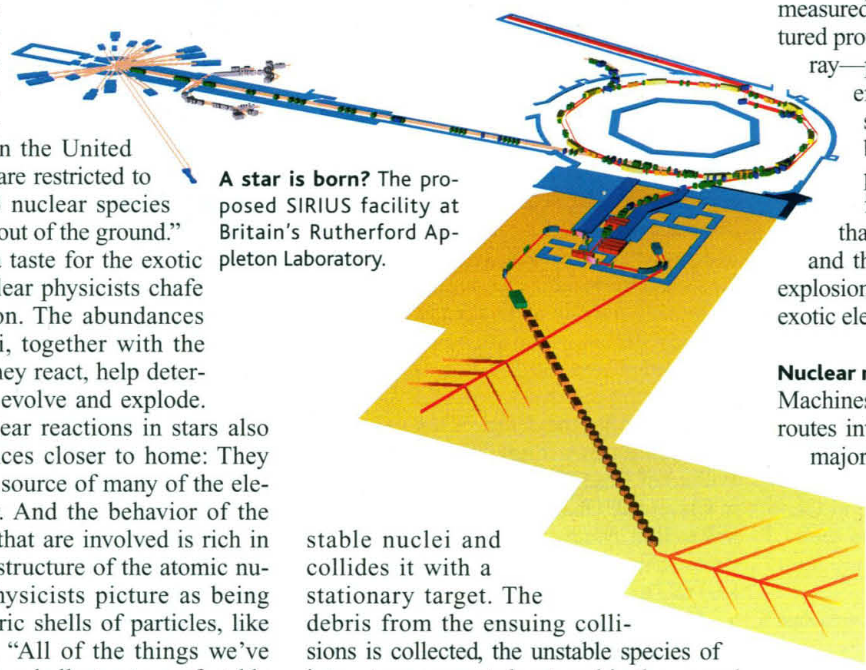
A new generation of accelerators capable of generating beams of exotic radioactive nuclei aims to simulate the element-building processes in stars and shed light on nuclear structure

Beaming Into the Dark Corners Of the Nuclear Kitchen

Imagine being a chef trying to re-create all of the world's cuisines with only flour, rice, potatoes, and yams as ingredients. That's the plight of physicists trying to probe the structure of the nucleus and explore the range of exotic nuclear reactions that take place in the cosmos. The hellish interiors of stars and supernovae and the surfaces of neutron stars, for example, are the scenes of frenzied nuclear cookery, where unstable nuclei overburdened with protons or neutrons collide or decay, spawning new, equally unstable nuclei. Thousands of different radioactive nuclei take part in these reactions. But as a physicist on Earth, says William Gelletly of the University of Surrey in the United Kingdom, "you are restricted to the roughly 283 nuclear species that you can dig out of the ground."



A star is born? The proposed SIRIUS facility at Britain's Rutherford Appleton Laboratory.

It's not just a taste for the exotic that's made nuclear physicists chafe at this restriction. The abundances of exotic nuclei, together with the rates at which they react, help determine how stars evolve and explode. The exotic nuclear reactions in stars also have consequences closer to home: They are the ultimate source of many of the elements we know. And the behavior of the unstable nuclei that are involved is rich in clues about the structure of the atomic nucleus, which physicists picture as being built of concentric shells of particles, like the atom itself. "All of the things we've learned about the shell structure of stable nuclei we expect to just be completely wrong in nuclei which are a long way from the stable nuclei," says Gelletly.

By colliding stable isotopes, physicists have been able to produce some exotic nuclei, but only in small numbers, providing tantalizing glimpses of the exotic nuclear structures and reactions that have been outside their reach. "The stable [nuclei] do not tell us too much about nuclear structure or nuclear synthesis, like in stars or supernovae," says Victor Ninov of Lawrence Berkeley National Laboratory in California. What's been needed was a way to create intense beams of radioactive nuclei, which could then be collided with other nuclei to mimic the nuclear recipe books followed in stars.

A new generation of accelerators is beginning to provide just that. A technique called isotope separation online, or ISOL, is being combined with a second accelerator stage to create powerful, bright beams of short-lived radioactive nuclei that can recreate previously inaccessible reactions and probe totally new nuclear species. The two-step technique essentially takes a beam of stable nuclei and collides it with a stationary target. The debris from the ensuing collisions is collected, the unstable species of interest are separated out, and in the second stage they are channeled into another accelerator to create a radioactive nuclear beam (RNB) that can collide with another target to perform an experiment.

At present, there are only two genuine ISOL-based RNB machines with accelerated beams in the world, one at Oak Ridge National Laboratory in Tennessee and one at the Catholic University of Louvain in Belgium. But physicists have quickly realized that such machines have the capability to transform nuclear studies. "It really is brand-new territory," says Michael Smith of Oak Ridge.

A case in point came this summer, with the first physics results from the Oak Ridge machine, the Holifield Radioactive Ion Beam Facility (HRIBF), which opened at the end of 1996. The team members there created a beam of a short-lived fluorine isotope, fluorine-17, by slamming a beam of light ions from their cyclotron into an oxygen-rich target. The fluorine ions, magnetically separated from the debris in the ISOL stage, were reaccelerated electrostatically as a radioactive beam. By driving the beam into a proton-rich target, Smith and his colleagues measured the rate at which fluorine-17 captured protons to yield neon-18 plus a gamma ray—part of a reaction chain that influences the violence of stellar explosions such as novae and x-ray bursts. The fluorine reactions bypass a slow nuclear reaction with a faster one, says Smith. "If you do that, you can generate energy faster, and that can affect the dynamics of the explosion"—as well as the amounts of other exotic elements it produces.

Nuclear reboost

Machines such as Holifield aren't the only routes into the realm of exotic nuclei. Four major sites across the globe are already producing a trickle of these nuclei by a technique known as fragmentation. It involves smashing a beam of fast, heavy ions into a target, then sorting out the fragments of the beam particle with a magnetic fragment selector and sending them to the experiment proper without reaccelerating them. The advantage of this approach is its ability to deal with isotopes that decay quickly, even in microseconds, while the ISOL approach needs many seconds to extract and sort the ions. The flip side is poor beam intensity and quality.

ISOL, which originated nearly 3 decades ago at CERN near Geneva, generates radioactive nuclei by smashing protons rather than heavy ions into a target, forging new nuclei that are then sorted from the debris magnetically. The original ISOL facility, called ISOLDE, did not accelerate these

CREDIT: COUNCIL FOR THE CENTRAL LABORATORY OF THE RESEARCH COUNCILS ions, however, so the resultant beam had very low energy—too low to simulate hot stellar interiors or drive nuclei together with sufficient violence to spark certain nuclear reactions. About 10 years ago, researchers realized that they could beat both these problems by reaccelerating the output of an ISOL device, resulting in a worldwide program to build ISOL-based RNB machines (see table). ARENAS, at the Catholic University of Louvain, fired up in the mid-1990s but still not fully operational, "was the first facility to reaccelerate these particles up to energies of interest, for example, for astrophysics studies," says Smith. Holifield, which was adapted from an existing heavy-ion facility, was hot on its heels.

MAJOR ISOL RADIOACTIVE BEAM FACILITIES

Location	Facility	Primary/secondary accelerator	Beam energy (MeV/nucleon)	Status
CERN, Switzerland	ISOLDE	synchrotron/unaccelerated	0.06*	operational since 1965
	REX-ISOLDE	synchrotron/linac	2	under construction for 2000
Oak Ridge	HRIBF	cyclotron/electrostatic	10	operational since 1996
TRIUMF, Canada	ISAC	cyclotron/linac	1.5	under construction for 2000
	ISAC-2	cyclotron/linac	12	proposed for 2004
Louvain-la-Neuve, Belgium	ARENAS	cyclotron/cyclotron	0.8	commissioning
Argonne	ATLAS	linac/linac	–	proposed
GANIL, France	SPIRAL	cyclotron/cyclotron	25	due to start 2000
Rutherford Appleton Lab, U.K.	SIRIUS	synchrotron/linac	10	proposed
U.S.	RIA	linac/linac	12	proposed for 2007?

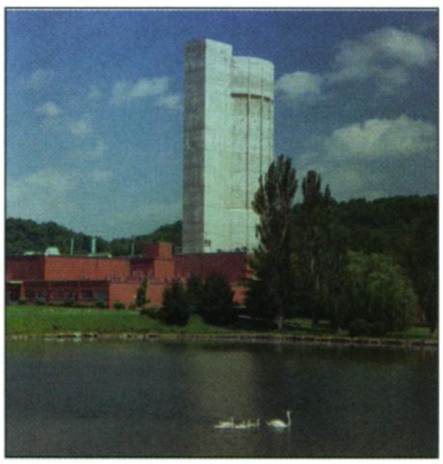
* Energy per nucleon number.

Now, researchers are converting other machines to make RNBs by bolting on a second accelerator stage. The TRIUMF accelerator center in Vancouver, for example, has already equipped an old cyclotron with an ISOL system, reports John D'Auria of Simon Fraser University in Vancouver. "In fact, it is probably the most intense ISOL system in the world," he says. The second-stage accelerator will soon be added. A small second accelerator is currently being added to the original ISOLDE at CERN, and Surrey's Gelletly is seeking backers for an RNB facility at the Rutherford Appleton Laboratory near Oxford, which will share a proton beam from the ISIS spallation source as its first stage. At the GANIL heavy-ion research lab in Caen, France, the SPIRAL dual cyclotron ISOL system has already been built and is awaiting approval to do physics.

Next up will be purpose-built facilities. This month, a U.S. task force led by Hermann Grunder, director of the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, will recommend building a half-billion-dollar, "second-generation" national RNB facility. And across the Atlantic, Björn Jonson of the University of Gothenburg in Sweden heads a similar group looking at pan-European options for a major RNB facility. Such a facility is the "obvious next step," says Jonson. "I think that it's a very high priority."

With this smorgasbord of new machines, nuclear physicists hope soon to move beyond their staple diet of stable nuclei and to start cooking up a storm of spicy new isotopes that will help them extend their theoretical picture of the nucleus. A key plank of nuclear theory is the shell model, according to which the combined quantum effect of the neutrons and protons—collectively known as nucleons—creates a set of energy levels in the nucleus, not unlike the energy levels that govern the movement of electrons orbiting it. A single shell comprises one or more levels of similar energy. This works well as far as it goes, but as soon as a nucleus gets packed with an excess of either neutrons or protons, the tidy shell picture starts to look too simple.

Simple geometry predicts a pretty constant density, so extra nucleons simply enlarge the nuclear radius by a one-third power law—just as adding a given volume of water expands a water balloon. Although stable nuclei obey this rule, early glimpses of unstable nuclei, obtained at fragmentation facilities, indicate that they deviate wildly. "One of the big surprises has been that for some nuclei at the limits of stability, their sizes do not at all follow our expectations," says Nigel Orr of France's nuclear and particle physics lab IN2P3. The isotope lithium-11, for example, is much larger than expected, compared with neighboring isotopes, says Orr.



Supernova simulator. Holifield is probing element creation in stellar explosions.

By monitoring the spread in the momentum of the fragments left when the nucleus breaks up following a collision, physicists have learned that this bloat in lithium-11 is due to the outermost or "valence" neutrons, which form a kind of neutron "halo" outside a dense nuclear core. Nuclear physicists have also found neutron halos in helium-6, beryllium-11, beryllium-14, and boron-17. Most recently, researchers from the four main fragmentation facilities have pooled results to demonstrate that carbon-19 also has a neutron halo, says Orr.

One step further on from neutron halos are neutron skins, the thin, neutron-rich surface layers surrounding a tightly bound nuclear core. Physicists believe that helium-8 probably has a skin of four neutrons and, according to Orr, "there is very good experimental evidence now that nuclei such as the very neutron-rich sodium isotopes have skins." A skin of nuclear matter would drastically alter the reactions between nuclei, says Gelletly, in ways that researchers hope to tease out at RNB machines.

"For the moment, we are trying to understand the interplay between structure and reaction mechanisms," says Gregers Hansen of Michigan State University in East Lansing. "With this in place, we can study the structure of as yet completely unknown nuclei far away from stability." In the process, researchers expect to find nuclear structures far more weird than the halos and skins they are now getting glimpses of. "To me, halos and skins are like pandas in the zoo. They are interesting animals to see, but the zoo is packed with many other species which are very exciting," says Witek Nazarewicz of the University of Tennessee, Knoxville. These exotica should have fundamental implications for physicists' understanding of

TABLE SOURCE: JERRY NOLEN, ANL, AND OTHER SOURCES; PHOTO CREDIT: OAK RIDGE NATIONAL LABORATORY the nucleus. Nazarewicz is at pains to point out that skins and halos are just the beginning, a first glimpse of a brave new neutron-rich world—"small consequences of this very big picture," he says.

Other items on physicists' RNB wish list include assessing the extent of the nuclear family. "What are the limits of nuclear existence?" asks Nazarewicz. On the chart of nuclei, plotted by neutron number versus proton number, stable nuclei occupy a broad stripe down the middle, with proton-rich nuclei above that stripe and neutron-rich nuclei below it. The extremes of the nuclear family are the so-called "drip lines" at the top and bottom of this broad swath of isotopes, marking out the limits beyond which protons or neutrons added to a nucleus simply "drip out." But these drip lines are far from well charted.

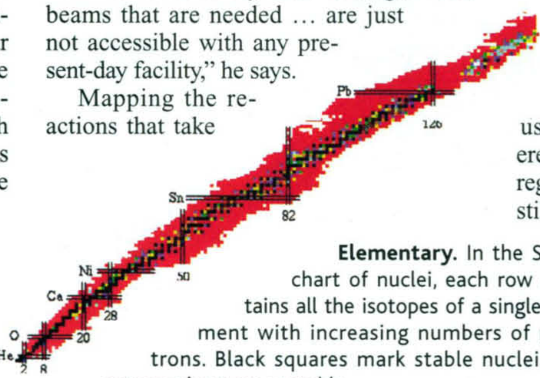
The neutron drip line is particularly fuzzy because nobody has had the means of mapping it out beyond the light nuclei, and theorists cannot agree on where it should go from there. For low-mass isotopes, the number of extra protons or neutrons needed to step out from stability to the drip lines is small—and within reach, using existing fragmentation machines. "With today's capabilities, the drip line has been explored up to isotopes of oxygen," Hansen says.

Beyond that, theorists predict wildly different drip lines, explains Philip Walker of the University of Surrey. "The calculations are rather delicate, and the neutron drip is not well established at all, even theoretically," he says. There may be thousands more nuclei on the high-neutron side of the chart waiting to be discovered, says Walker. Stepping out toward the neutron drip line for the heavier elements means colliding species that between them have enough neutrons to make one of these exotics, something that is only possible using RNBs. "There is no way to approach the very neutron-rich nuclei using stable beams and stable targets," says Nazarewicz.

Although the neutron drip line is exotic territory, it has direct implications for the genesis of many stable elements. The lightest elements—hydrogen, helium, and lithium—date from the big bang. But others were made in the nuclear furnaces of stars, then flung into interstellar space during supernova explosions. Astrophysicists are pretty confident that they understand some of the element-forging processes, such as the slow neutron capture cycle, or s-process, in red giant stars, in which nuclei can acquire neutrons at a rate of perhaps one a year. The nuclei later beta-decay, shedding an electron and changing a neutron into a proton, on the road toward creating elements such as iron.

Astrophysicists are less confident about rapid neutron capture, the r-process, which is thought to take place in supernovae. In the r-process, a nucleus can take up one or more neutrons every second and can rapidly march all the way out toward the neutron drip line before it beta-decays and moves one rung up the ladder of elements. Only by forging sufficiently neutron-rich—and therefore highly unstable—species will astrophysicists be able to explore the r-process sequence, explains Jerry Nolen of Argonne National Laboratory near Chicago. "The beams that are needed ... are just not accessible with any present-day facility," he says.

Mapping the reactions that take place close to the drip line will help astrophysicists refine their picture of element formation in supernovae, thought to be the ultimate source of most of the heavier elements all the way out to the end of the periodic table. Understanding the complex reactions in supernovae and other cosmic processes requires knowing at least something about the thousands of contributing nuclear processes. "In the laboratory, you make nuclear measurements of how fast things fuse together ... and that's basically input information into a theoretical model of how these systems might explode," says Smith. "And then you compare the output of that model with [astronomical] observations and try to get the two to match up."



Elementary. In the Segré chart of nuclei, each row contains all the isotopes of a single element with increasing numbers of neutrons. Black squares mark stable nuclei, red squares the most unstable.

As well as exploring the drip lines, researchers also want to venture beyond the very topmost point of the table, the realm of so-called superheavy elements, which do not exist in nature and can only be produced in the laboratory. A number of labs across the globe are already actively trying to create new superheavy elements, and so far this year they have claimed discovery of three previously unknown elements: 114 (*Science*, 22 January, p. 474), 116, and 118 (*Science*, 11 June, p. 1751). This is not just nuclear stamp collecting, however. The teams are trying to confirm an important prediction of the shell model.

Physicists already know that a nucleus gains stability if it has the right number of protons or neutrons to fill a shell completely. Even being close to one of these "magic numbers" confers some extra stability. Oxygen, calcium, nickel, tin, and lead all have magic numbers of protons, so these elements tend to have larger numbers of stable isotopes than do nearby elements. Some shell theorists predict a magic number at 114. By synthesizing element 114 and the nuclei around it, physicists hope to find out if there is indeed an "island of stability" in this region of the table of nuclei.

And radioactive beams will be critical to exploring this island. That's because the stablest superheavy nuclei tend to be more neutron-rich than lighter elements are. Fusing two lighter stable nuclei—now the standard way to make superheavy nuclei—yields a neutron-poor, and hence unstable, superheavy nucleus. "The superheavies they have discovered are at the bottom edge of the predicted region of stability, where the half-lives are still extremely short," says Nolen. "If you can really get up into the center of the region of stability that's predicted, the half-lives may become days or years." Existing facilities can't get off the beach and into the interior of the island of stability, explains Nolen. Creating beams of neutron-rich nuclei at an RNB facility is the only way forward.

Nucleus as superbattery

Exploring the island of stability promises the thrill of fundamental discovery, but other goals of RNB research could have practical value: energy-dense nuclear "batteries," for example. Pump energy into an atom to excite one of its electrons and the atom, now unstable, will dump that excess energy as fast as possible and drop to a lower energy state. A nucleus can also absorb energy—much larger amounts, because nuclear forces are vast compared to those binding electrons to atoms—which can go into winding up the spin of the nucleus. This energy and any extra spin are normally lost promptly when the nucleus emits a photon. But the nucleus of one natural isotope, tantalum-180, was left engorged with so much extra spin when it was forged and energized billions of years ago in a supernova explosion that it cannot shed the energy via a single photon. As a result, tantalum-180 is caught in a near-eternal excited state, with a lifetime so long it has never been measured. It is nature's only example of a spin trap, says Surrey's Walker.

But researchers can make other, less permanent spin traps in the laboratory. One is tantalum-180's neighbor, hafnium-178. It has a spin trap state with a half-life of 31 years that can deliver a giant 2.4 mega–electron volts when it decays, in the form of a jolt of gamma rays, with the added bonus that the ground state is stable (*Science*, 5 February, p. 769). "That's the sort of state I

CREDIT: OAK RIDGE NATIONAL LABORATORY/DOE like," says Walker. In principle, such spin traps offer a kind of stored nuclear energy with no radioactive waste. "If you could make a kind of superbattery that you could take into space with you and power your space station for 5 years, all in a kilogram box or something, it would be pretty useful," notes Walker.

Almost by definition, however, trapped energy is hard to release, but that's where RNBs come in because of their ability to make new spin traps. "The ones we can make at the moment are not the best ones that are predicted theoretically," says Walker. Recent studies have hinted that it may be possible to create nuclear spin traps that could be triggered to offload their excess energy using a laser beam, he adds.

Such nuclear cookery—and much more—will be made possible with the extra ingredients provided by RNB machines of the future. And those same machines will show nuclear structure researchers just how the nucleus, that cauldron of nucleons, seethes and stews and, in some cases, boils over. **–ANDREW WATSON**

Andrew Watson writes from Norwich, U.K.

BIOMEDICAL RESEARCH

Ethical Loophole Closing Up For Stem Cell Researchers

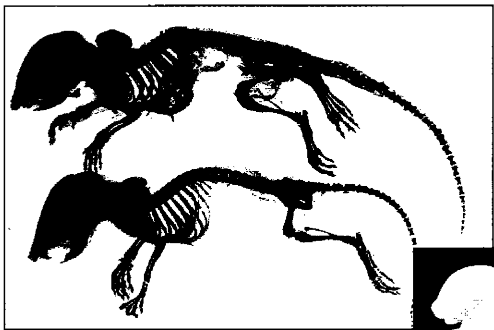
Embryonic germ cells, derived from fetuses, are less ethically contentious than their stem cell cousins. But they may not hold the same promise

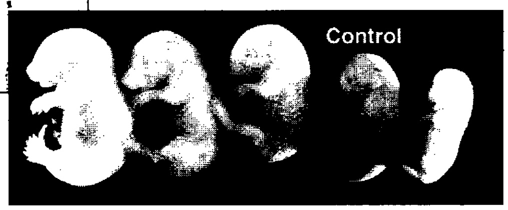
MUNICH—In the rapidly growing field of stem cell research, the demands of science and those of medical ethics are colliding head on. Ever since U.S. researchers revealed last year that they had created "immortal" lines of human embryonic stem (ES) cells—a type of cell extracted from an embryo that can be tweaked to grow into any form of human tissue (*Science*, 6 November 1998, p. 1014)—teams around the world have been eager to use ES cells to grow tissues for transplant. But creating ES cell lines requires researchers to destroy an embryo, so research is either heavily restricted or banned altogether in many countries. One hope was that lines of embryonic germ (EG) cells, which are taken from aborted fetal tissue, could be used instead. But results presented at a workshop on stem cell and nuclear transfer research here last month have dampened those hopes.

EG cells are derived from primordial germ cells, which later in development give rise to eggs or sperm. Like ES cells, they regenerate seemingly forever, and researchers can coax them to differentiate into any type of tissue. Because of this apparent similarity between EG and ES cells, the DFG, the main research funding agency in Germany, where the production of human ES cells is banned, has advised scientists to use EG cells for their research.

But work presented by Azim Surani of the Wellcome/CRC Institute of Cancer and Developmental Biology in Cambridge, U.K., casts strong doubt on the assumption that EG cells can simply be substituted for ES cells. It shows that when mouse EG cells are implanted into early mouse embryos, the tissues containing the cells develop abnormally. This happens because the genes in the EG cells lack certain modifications needed for their normal activity during development. For many at the meeting, Surani's data cast doubt on the suitability of EG cells as a source of transplant tissues. "This report has discouraged German researchers from staking everything on this one chance," said Anna Wobus of the Institute for Plant Genetics in Gatersleben.

As part of his ongoing studies of germ cells, Surani had decided to test whether the development potential of EG cells is equivalent to that of ES cells. As a pioneer of research into a phenomenon called imprinting, he had reason to be concerned that it might not be. During the formation of the sperm and egg, some genes undergo a type of biochemical modification known as methylation that selectively inactivates the paternal or maternal copies of a gene, so that both are not active at once in the developing embryo and adult. The gene imprints imposed by the male and female are different, and both types must be present when the egg and sperm come together if normal development is to occur. But before that imprinting can occur, the original imprints inherited by an embryo have to be erased—a change that happens in the primordial germ cells. So Surani reasoned that if an EG cell line is derived from germ cells with their imprints absent, the cells may not develop normally. And that's what he and his colleagues found.





Lost hope. Making chimeras with EG cells leads to skeletal deformations (top, upper image) and oversized fetuses (left three in lower image).

When ES cells are injected into early mouse embryos, the tissues appear to form normally. But when the researchers injected EG cells into the preimplantation embryos of naturally mated mice, the EG cells that became incorporated into the tissues of the developing chimeras caused them to grow bigger and heavier than controls and the embryos also suffered from skeletal abnormalities.

Hints that these problems are due to lack of imprinting in the EG cells came when Surani's team transplanted EG cell nuclei into egg cells that had their own nuclei removed. The resulting embryos were small and had abnormal placentas. When the researchers tested for expression of particular genes that should have been imprinted, they found that both parental copies were either completely repressed or that both were active in the embryos, indicating that lack of imprints was at least part of the problem. In another experiment, Surani's team fused white blood cells and EG cells and found that several imprints were erased from the blood cell nucleus—implying that EG cells can still erase imprints even in mature cells.

The question now is whether human EG cells will suffer from the same problems as the mouse cells. If so, it might be possible to avoid the problems by harvesting the cells while they retain their imprints. Despite that possibility, Surani's results came as a blow to German stem cell researchers for whom working on human EG cells is the only legally permitted alternative. DFG Vice President Rüdiger Wolfrum of the Max Planck Institute for International Law in Heidelberg says: "This may mean that certain research projects ... have to be conducted abroad."

–SABINE STEGHAUS-KOVAC

Sabine Steghaus-Kovac writes from Frankfurt.

CREDITS: A. SURANI, WELLCOME/CRC INSTITUTE OF CANCER AND DEVELOPMENTAL BIOLOGY