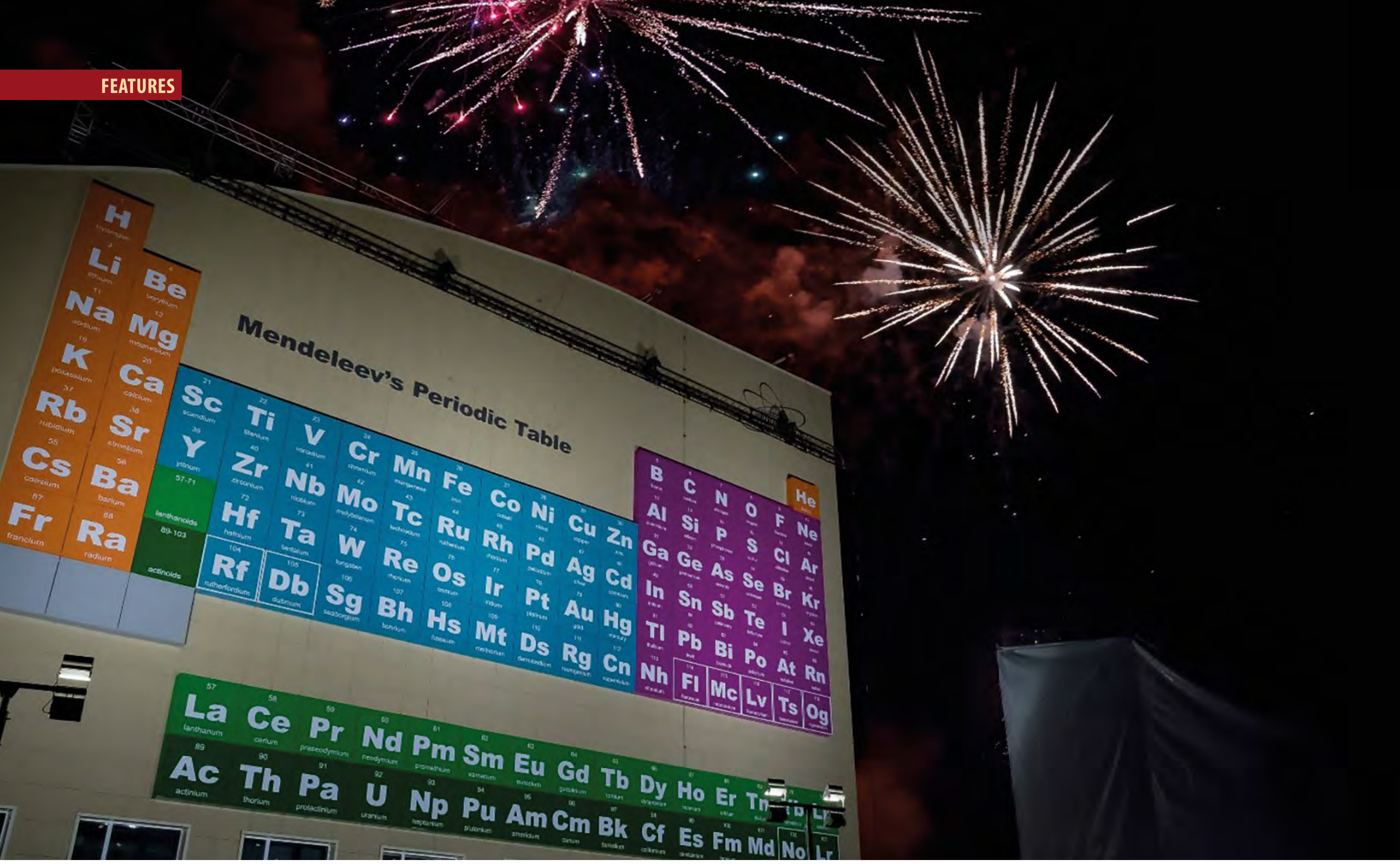

PATHWAYS TO NEW EXOTIC NUCLEI

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The challenge of today's nuclear physicists is to extend the nuclide chart. We produce and study exotic nuclei to understand the nature of the nuclear force, the origin of chemical elements in the universe and the energy production and evolution of stars. Beyond, exotic nuclei are used in various applications like medicine or compact power sources.

Ernest Rutherford's discovery of the atomic nucleus started the era of nuclear physics. While in Rutherford's days barely 300 different nuclides of 92 elements were known, the present Karlsruhe chart of nuclides comprises more than 3000 isotopes of 118 elements (Figure 1a). Model predictions indicate that another 4000 nuclides are awaiting their discovery, the vastest still unexplored area being located on the neutron-rich side of the upper half of the nuclide chart. Nowadays it is the most exotic nuclei, with a large surplus or deficit of neutrons, or large numbers of up to 300 nucleons, which keep nuclear physicists busy, and there are many good reasons for that.

Why does one produce new atomic nuclei?

Each nuclide has its individual combination of protons and neutrons (nucleons). Its properties like binding energy, half-life, shape or radioactive decay mode are governed by the sensitive interplay between the attractive nuclear force and the repulsive Coulomb force. What we call "nuclear force" is actually the long-range part (>1 fm) of the strong interaction, while the short-range part (<1 fm) confines quarks and gluons inside the nucleons. The description of the nucleon-nucleon interaction within quantum chromodynamics would be crucial for a grand unification theory, a quantum field theory unifying the electromagnetic, the weak and the strong interactions. In particular, very exotic nuclei are highly desired to provide new input data for theoretical models.

Understanding the origin of the chemical elements is one of the biggest challenges in science. Nuclear physics research has provided a broad picture of element creation [1], but many holes in that picture remain. We still do not know the main astrophysical site for nucleosynthesis of heavy elements. Possible scenarios include supernovae explosions and merging neutron stars. The latter events are also sources of gravitational waves that may provide useful information about element creation. Many questions about element creation will be addressed by a new generation of nuclear research facilities where atomic nuclei of great relevance for galactic chemical evolution will be produced and probed.

How does one produce new atomic nuclei?

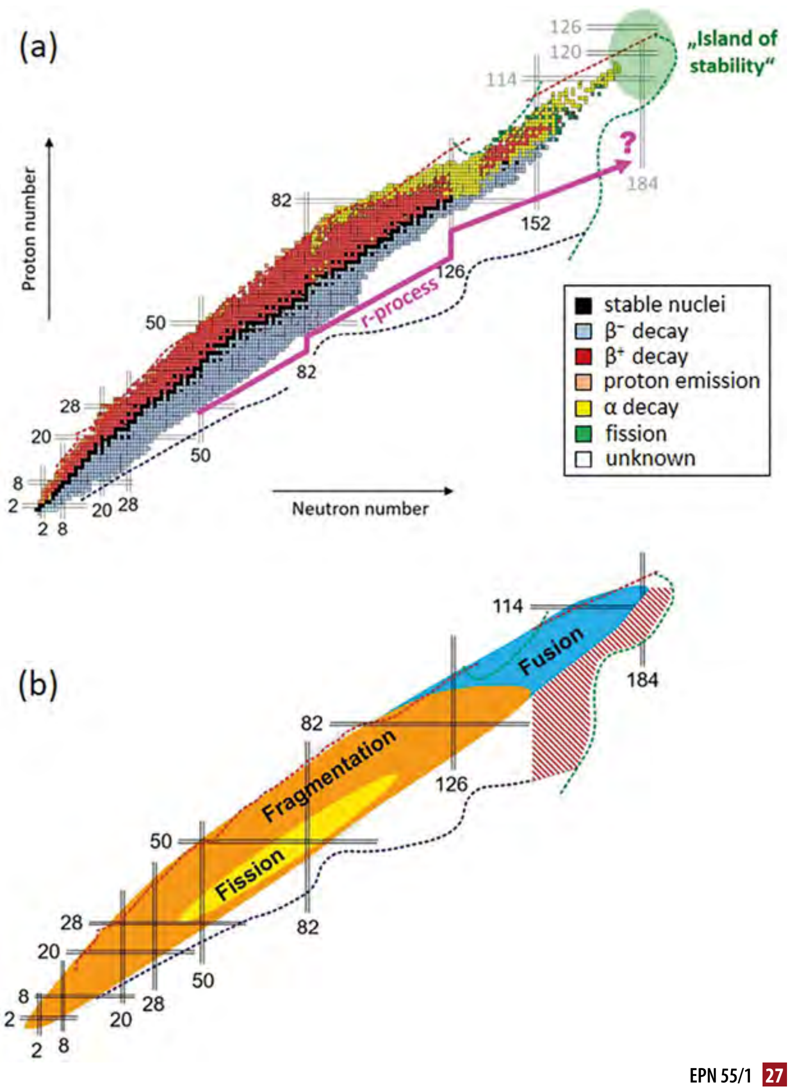
Exotic nuclei are produced in nuclear reactions of which we use four basic types in laboratory nucleosynthesis (Figure 2). One of the heaviest applicable projectile and target nuclei is the uranium isotope ^{238}U which contains 92 protons and 146 neutrons. Nuclei lighter than uranium are produced in fission or fragmentation reactions. Fission of uranium and similar heavy elements can be induced by thermal neutrons or fast projectiles like protons and results in two intermediate heavy, neutron-rich nuclides with nucleon numbers around A=100. Fragmentation reactions occur when a heavy nucleus collides with a light nucleus at high energies where the projectiles are accelerated to velocities of about 90 % the speed of light. During the collision the heavy reaction partner breaks up in two or more smaller pieces. Fragmentation is suitable to produce neutron-rich as well as neutron-deficient nuclei and is to date the most widespread reaction type to create exotic nuclei in the region below uranium.

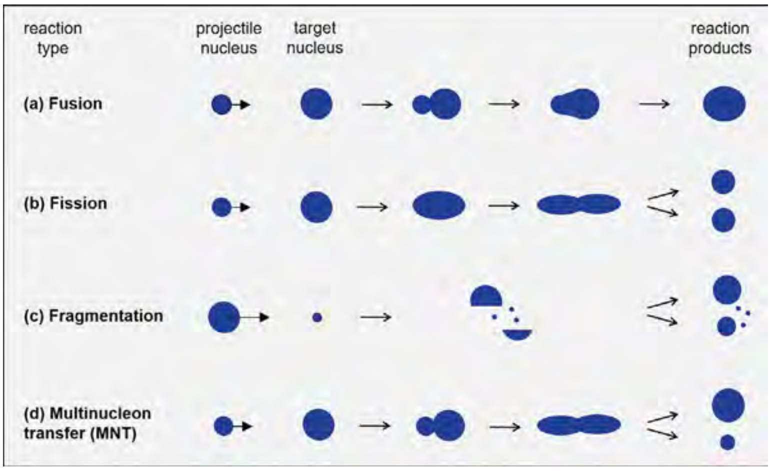
Exotic nuclei with more than 92 protons are synthesized in fusion reactions. The bottleneck of fusion is that it leads to neutron-deficient nuclei. This is the main reason why the neutron-rich transuranium and superheavy element region is still unpopulated. The fusion process of heavy nuclei is strongly influenced by the repulsive Coulomb force between the interacting nuclei, which counteracts the attractive nuclear force. In many cases the nuclei separate before fusion is completed. Before separation they can exchange large numbers of nucleons, which is termed as multi-nucleon transfer (MNT). After separation, a projectile-like and a target-like nucleus are emitted which can have very different proton/neutron numbers compared to the original nuclei. Nowadays, MNT reactions attract increased attention in the nuclear physics community, because they might be a pathway to populate the hatched area in Figure 1b [2].

Where does one produce new atomic nuclei?

Figure 3 shows a selection of existing and upcoming exotic ion facilities worldwide. The impressive number of labs reveals the high relevance of the research field. Most labs focus on exotic nuclei in the region below uranium which they produce typically in fragmentation and fission reactions. Two basic techniques are applied [3]. The ISOL (Isotope Separation OnLine) technique uses high-energy (~1 GeV) proton beams to induce reactions in heavy target nuclei. The other method is called In-flight technique and uses fragmentation or fission of heavy projectiles which are accelerated to energies of several 100 MeV/nucleon up to 1 GeV/nucleon before they interact with targets of light elements like beryllium or carbon. The (exotic) fragments emerge with relativistic energies • • •

▾ **FIG. 1: (a)** The current Karlsruhe Chart of Nuclides contains almost 3,300 different isotopes of 118 elements. The expected limits of nuclear stability (driplines) are indicated by dashed lines. Toward the driplines, the nuclei become more exotic and unstable. The still unknown nuclei along the magenta-coloured line participate in the astrophysical rapid neutron capture process (r-process) which contributes to the creation of the heavy elements in the universe. **(b)** Fragmentation, fusion and fission are presently the standard reactions to produce (new) isotopes in the lab. The chart shows the typical areas that are populated with these reactions. The blank area inside the neutron dripline can principally be populated in fragmentation reactions, but the respective nuclides have not yet been discovered. The red-white hatched area is principally not accessible with fusion, fission or fragmentation reactions.





▲ **FIG. 2:** Illustration of the different reaction types used for nucleosynthesis in laboratory.

• • • and are strongly forward-directed which enables their separation with an In-flight separator.

A facility with long tradition is ISOLDE at CERN. It is in operation since 1967 and uses the ISOL technique to produce exotic nuclei. There is an impressive variety of experiments at ISOLDE. Ultra-precise mass measurements in a Penning trap system reveal the binding energy of exotic nuclei. Laser spectroscopy of electronic states reveals the ground state properties like spin and electric and magnetic moments, or the charge radius of the nuclei. Coulomb excitation of post-accelerated exotic ions reveals their nuclear structure in gamma spectroscopy experiments. Finally, exotic nuclei are used in solid state physics experiments or produced for cancer diagnostics and therapy, for example, some neutron-deficient terbium isotopes. Also the Fragment Separator (FRS) facility at GSI Helmholtz Center (Germany) has a long tradition. It applies the in-flight technique to create exotic nuclei in fragmentation and fission reactions. In more than 30 years of operation about 300 new isotopes were discovered at FRS to date. In the years to come, the FRS will be followed by the new Super-FRS facility as a part of FAIR/GSI.

Presently, existing facilities are being upgraded with respect to higher beam intensities and efficiencies of separation and detection techniques. But there are also newcomers. Among them, the Radioactive Isotope Beam Factory RIBF at RIKEN (Japan) is to date the most powerful new-generation In-flight facility which provides the highest primary beam intensities. Recently, also the Facility for Rare Isotope Beams FRIB at Michigan State University (USA) has started operation. Several further new facilities are under construction (see Figure 3 and ref. [3]).

Besides, there are facilities which focus on the synthesis of new superheavy nuclides. Labs with long tradition in this field are GSI, the Joint Institute for Nuclear Research JINR (Russia), the Lawrence Berkeley National Lab LBNL (USA) and RIKEN [4,5]. At JINR, the brand-new *Superheavy Element Factory* recently went in operation. It was built to deliver and work with up to 30 times higher beam intensities during 290 days per year. A major goal is the synthesis of new elements with 119 and more protons.

In summary, the extension of the current chart of atomic nuclei to exotic isotopes is at the core of research activities in nuclear physics facilities worldwide. The understanding of the properties of exotic nuclides, using nuclear reaction mechanisms along with innovative techniques and novel theoretical approaches, will help us to answer fundamental questions about the nucleon-nucleon interaction, the creation of chemical elements in the universe and to use these nuclides to improve our well-being. ■

▼ **FIG. 3:** Selection of existing and upcoming facilities to produce and study exotic nuclei.

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