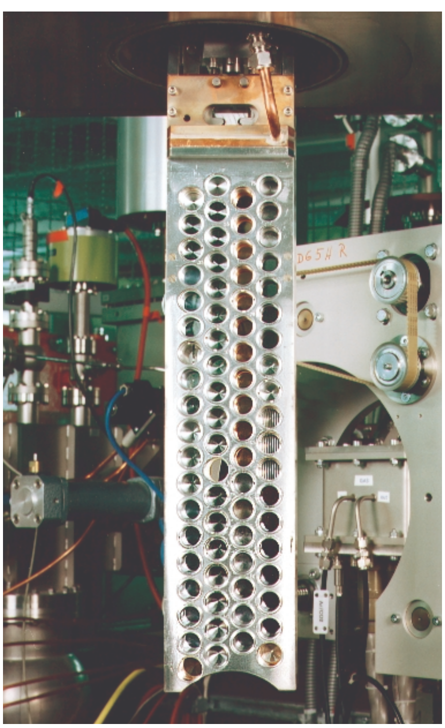
Relativistic Beams of Exotic Nuclei

A Powerful Tool for Nuclear Structure Physics

A total of 75 targets of different elements with differing thicknesses can be installed at the target station at the entrance of the fragment separator. Each of the cylindrical targets, which have a diameter of two centimeters, can be moved into the path of the ion beam with millimeter precision using step motor control. If required, the target holder can also be exchanged by remote control.



The production of exotic nuclei beyond the region of nuclei known today, and the study of their properties have a long tradition at GSI. The best-known examples are the experiments to synthesize the heaviest elements—those with atomic numbers 107 to 112. Besides the structure of such exotic nuclei, such investigations also focus on astrophysical questions such as the stellar nucleo-synthesis. Since the addition of the SIS heavy ion synchrotron to the GSI facilities, the most important tool for these experiments has been the fragment separator, where relativistic beams of exotic nuclei can be produced and separated into isotopically-pure components. In conjunction with the ESR experimental storage ring and the various experimental facilities in the target hall, this facility has opened up unique opportunities for nuclear structure research. Moreover, these opportunities will be considerably extended in the course of the present intensity upgrade programme. GSI will thus be able to strengthen its position as one of the world's leading laboratories as far as the study of radioactive secondary beams is concerned.

So-called "magic" nuclei have a special significance within the landscape of the nuclides. In a manner analogous to the shell structure of the electrons surrounding the nucleus, the protons and neutrons making up the nucleus also form closed shells at particular proton and neutron numbers. Such closed shells lead to particularly stable configurations—the so-called magic nuclei. If both the proton and the neutron numbers are magic, then the nucleus is said to be doubly magic, and holds a special fascination for nuclear physicists. Thus, the ability to correctly predict shell closure is an important test for nuclear models, particularly when the nuclei concerned are far off stability. Physicists believe that the study of these and neighboring nuclei offers especially clear insight into the effective interaction between the nucleons.

„Magic" Nuclear Physics

The first production and identification of the doubly magic nuclei tin-100 [1] and nickel-78 [2] thus belong to highlights achieved to date at the fragment separator, the importance of which may be compared to the synthesis of the heaviest elements at the UNILAC. Moreover, it may prove possible to produce a further doubly magic nucleus, nickel 48, in coming experiments at the fragment separator. With 28 protons and just 20 neutrons, this nucleus has such an extreme surplus of protons that its observation would, in itself, be a little scientific sensation. The production and investigation of such magic isotopes and their neighbours, far off the valley of stability, will thus continue to be one of the central issues of the experimental programme at the fragment separator.

But there is more to nuclear physics than magic or even doubly magic nuclei. To take but one example, the question of the location of the boundaries within which matter can exist at

The Fragment Separator

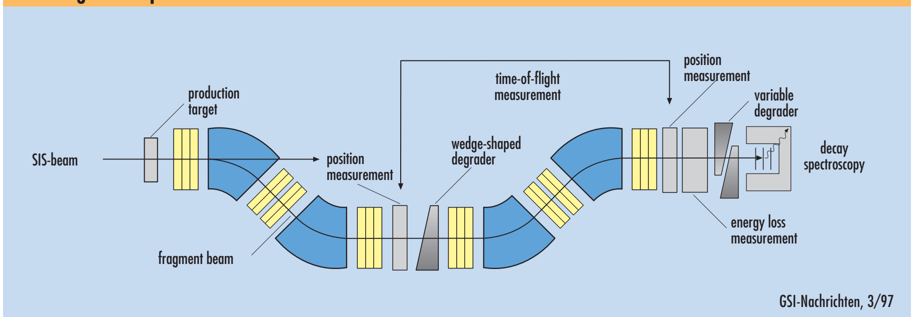


Figure 1: The fragment separator consists of a combination of magnetic dipoles (green), which deflect the fragments, and magnetic quadrupoles (yellow), which serve to focus the fragment beams. A so-called degrader (blue)—in practice an aluminum wedge in which the fragments are slowed down in proportion to the square of their nuclear charge—can be introduced in the mid-plane. The combination of momentum selection, energy loss, and repeated momentum selection produces an isotopically pure separation at the exit of the fragment separator.

all, even for a short lifetime, is of fundamental importance. If, for example, physicists create nuclei with increasing proton surplus in comparison to the stable isotopes of the same element, eventually a boundary is reached—the so-called proton drip line—beyond which a further proton no longer remains bound to the nucleus. In the case of nickel-48, it is not known whether or not the isotope can exist in bound form. In the same way, extremely neutron-rich nuclei are subject to the constraint of the neutron drip line.

In the region of the drip lines a series of new and interesting phenomena occur. Light elements with a high neutron surplus such as lithium-11 show a strongly increased nuclear radius. In this nucleus, the outer, weakly bound valence neutrons form a diffuse cloud around the core of the nucleus, a so-called neutron halo. An analogous, but much weaker halo effect has also been observed for extremely proton-rich nuclei such as boron-8.

Information on neutron-rich isotopes is especially interesting for astrophysics. Today, we know that the process of nucleo-synthesis in the interior of stars and in the course of supernovae explosions proceeds via exotic nuclei. Neutron-rich nuclei along the path of the so-called r-process play an important role in the formation of the heavy elements. These nuclei are formed by rapid (r) neutron capture during the course of supernovae explosions. The better-known the properties of these neutron-rich isotopes, the more exactly nucleo-synthesis in such astrophysical processes can be modeled, and important variables such as the neutron flux density in the "element kitchen" of a supernova can be determined. One important criterion for the reliability of the model is how accurately it reproduces the observed relative abundances of the different elements.

The following discusses the production of exotic nuclear beams at the fragment separator in more detail, with consideration of the different reaction mechanisms and the separation techniques utilized at this, one of the most important instruments for nuclear structure physics at GSI. Related reports on the broad research programme of experiments at and in connection with the fragment separator have already appeared in previous issues of GSI-Nachrichten (4/96, 5/96, 6/96 and 1/97).

Prior to the construction of the SIS heavy ion synchrotron, nuclear reactions at low energies around the Coulomb barrier were used to produce exotic nuclei at GSI. These reactions, which were studied at the UNILAC, populate a relatively small region of the chart of nuclei around the nucleus to be synthesized. The situation is different, however, in the case of high-energy reactions, which were first used experimentally at the BEVALAC in Berkeley during the '70s. When relativistic ions, accelerated to almost the velocity of light, collide with a thick target, a broad spectrum of nuclei with mass and charge numbers below those of the projectile nucleus fly onward, close to the velocity of the primary beam. An exotic nucleus can be separated from this mixture almost free of background. This is accomplished by deflecting the ions in electromagnetic fields and, in addition, slowing them down in thick layers of matter. This is the basic principle of the FRS fragment separator at GSI, which is illustrated schematically in Figure 1 [3].

Fragmentation or Fission

When a projectile travelling at relativistic velocity hits a target nucleus, two distinct geometrical zones can be distinguished in the reaction: the region where the two colliding nuclei overlap, in which the nuclear matter is compressed and heated, and the "spectator matter" which remains comparatively unaffected. To put it more clearly, the "spectator matter" is sheared off from the projectile nucleus in the collision. This remnant of the projectile, which continues in the original beam direction with practically unaltered beam velocity, must rearrange itself corresponding to the remaining numbers of protons and neutrons. The energy released in this process is dissipated by boiling particles off—mostly neutrons in the case of heavy nuclei. The distribution of fragmentation products is thus centered on the neutron-poor side of the valley of stability. Both the experiments in Berkeley and the systematic studies carried out during the first years of operation of the FRS at GSI have shown that the fall-off in the probability of fragments formation on the neutron-poor side follows approximately a Gaussian distribution. The probability of formation decreases by approximately one order of magnitude for each missing neutron (Figure 2).

In order to produce the neutron-rich isotopes so relevant to the astrophysical questions mentioned above, another type of nuclear reaction can be utilized at the FRS: the projectile fission of relativistic heavy ions. When a projectile nucleus does not collide directly with a target nucleus, a fragmentation reaction cannot occur. If, however, the nuclei pass extremely closely, they can be excited by the Coulomb field between the projectile and target nuclei. In the case of heavy projectiles such as uranium, this excitation can cause the nucleus to undergo fission. Due to the fact that the stable isotopes of heavy ions are neutron-rich, the fission fragments produced in this manner lie on the neutron-rich side of the valley of stability (Figure 2 and 3). One especially interesting feature of this process is the large number of new exotic nuclei that can simultaneously be produced and identified. One such nucleus is the doubly magic nucleus nickel-78.

Separation and Identification

The fragment beam of the FRS contains a complex mixture of different ions travelling at almost the same velocity. Magnetic dipole fields are normally used to separate the different ion species from one another according to their mass to charge ratio A/Q. Magnetic quadrupoles are used to focus the fragment beams.

The FRS consists of a total of four groups of dipole and quadrupole magnets. Each dipole deflects the beam by an angle of 30 degrees. The magnetic fields are normally set so that an achromatic focus is produced at the output of the fourth stage. Here, the ions with the same mass to charge ratio are focused into a small area, regardless of their initial angle or momentum. Naturally, such an ion-optical arrangement does not allow separation of a single isotope, as all ions with the same ratio of mass to charge are allowed to pass. To separate this mixture of isotopes according to nuclear charge number, the ions must be passed through thick layers of matter, where they lose energy. The energy loss is dependent on the nuclear charge number of the fragment. The principle is particularly advantageous at high beam energies, such as those delivered by the SIS heavy ion synchrotron. At these energies, all light and medium-heavy, and most heavy nuclei are completely ionized, i.e. their ionic charge is equal to their nuclear charge. In addition, the relative smearing-out of the velocity and the angular straggling during the passage through matter is low, enabling material thicknesses of several centimeters to be used without significantly enlarging the beam focus.

In practice, a wedge-shaped “degrader” of aluminum is used in the central plane of the FRS. An isotopically pure beam with a diameter of a few centimeters can be produced at the output. In order to further increase the degree of confidence with which the isotope can be identified and interfering isotopes can be separated, the position and flight time of the ions in the second half of the separator and their energy loss are measured in suitable detectors. Both the nuclear charge and the mass of the ions can be obtained from this data. In this way, the observed ions can be individually identified, so that even extremely rare nuclei can be tracked down like a needle in a haystack.

The process is highly efficient. For ion beams of exotic nuclei produced by means of projectile fragmentation, the transmission through the fragment separator reaches over 90 percent. The decisive factor here is that the fragments almost completely retain both the direction and velocity of the primary ion beam. In contrast to this situation, during the projectile fragmentation of uranium, energy is released and transferred to the fragments, changing their velocity and direction. Transmission of such beams through the fragment separator is thus limited to around 10 percent. On the other hand, this leads to an advantage: If the FRS is set to select only such nuclei with velocities higher than that of the ions colliding with the target, then only nuclei formed by fission are selected.

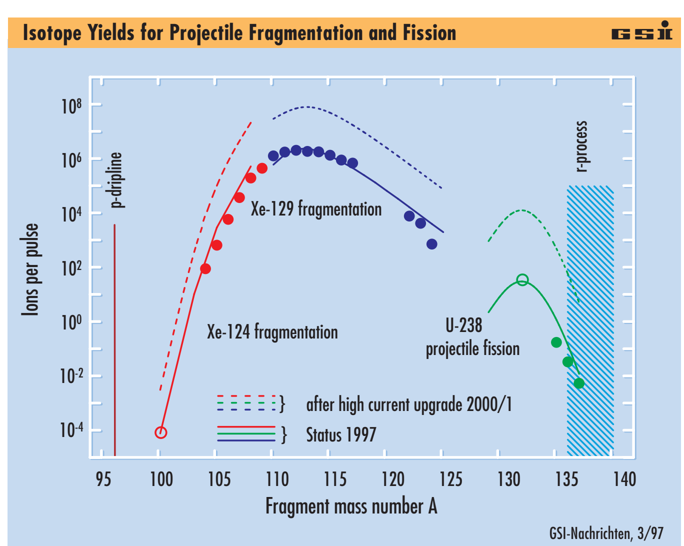


Figure 2: Isotope yields for projectile fragmentation of ^{124,129}Xe (red and blue points) and fission of ^{238}U (green points). The dashed lines show the intensitites expected after the intensity upgrade. The line on the left marks the proton drip-line, the dashed area on the right shows the region of nuclei relevant for the r-process.

In comparison to on-line mass separation using conventional ion sources, the process employed at the FRS has the advantage that the chemical properties of the isotopes so produced are irrelevant. For example, the isotopes of the element tungsten, which is difficult to vaporize, can be produced in the same way as those of the volatile element mercury.

These advantages of the fragmentation process, the possibility of pure separation and clear identification, high efficiency, and universality formed the foundation for the major successes of the fragment separator mentioned at the beginning of this article. During the experiments yielding the first detection of tin-100 and nickel-78, it thus proved possible to identify a few nuclei of these isotopes out of a background of more than 10^{12} other nuclei.

After the Intensity Upgrade

The experiments at the fragment separator will benefit particularly from the planned increase in intensity of the SIS heavy ion synchrotron. Nuclei which were previously only available in extremely small amounts will be produced in such numbers that it will be possible to use them for mass measurements in the ESR and other spectroscopic studies. Experiments of this type are already planned, especially for tin-100 and for the astrophysically interesting nuclei around nickel-78.

Linked with the intensity increase are higher technical demands on the infrastructure and on the operation of the fragment separator, for example in the area around the target station due to the increased radioactive activation, or in data acquisition, due to the much-increased data rates. The corresponding measures are currently being implemented, so that the intensity increase available as of the middle of next year can be fully utilized. In connection with the storage ring and the experimental facilities in the target hall, this will allow GSI's leading role as a laboratory for relativistic radioactive beams to be consolidated and extended even further. ■

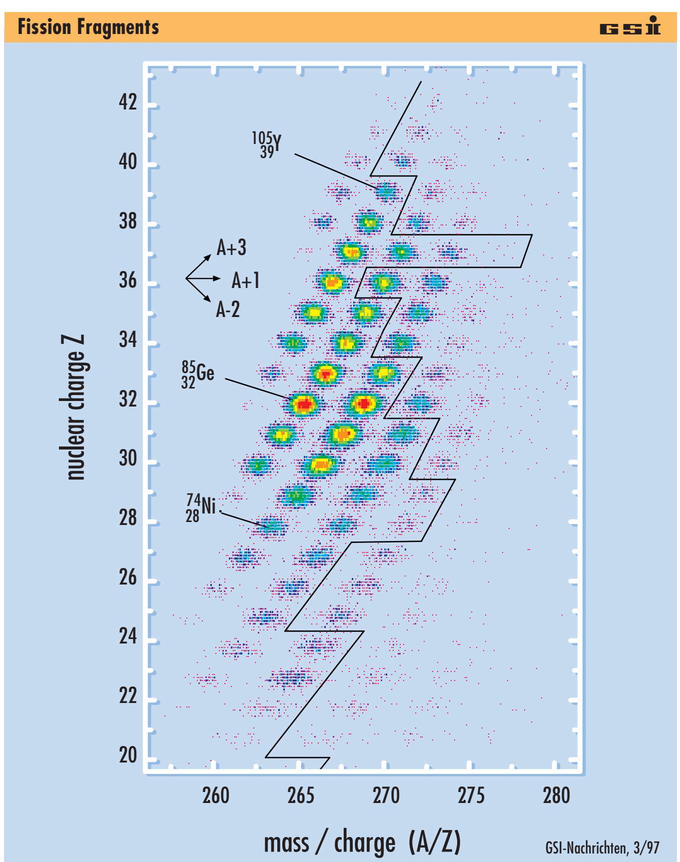


Figure 3: The figure shows the isotopic distribution of uranium fission fragments recorded at the fragment separator. To unambiguously identify a nucleus, its energy loss in a special detector is plotted against its time of flight. The energy loss determines the nuclear charge, the time of flight offers a measure of the nucleus' mass. Some 300,000 events recorded over just 10 hours of measuring time are plotted in the figure. All the nuclei to the right of the solid line were dicovered during this experiment. In fact, a total of over 100 new isotopes were identified using projectile fission at the fragment separator.

LITERATURE

[1] R. Schneider et al.: Z. Phys. A348, 221 (1994) und Physica Scripta T56, 67 (1995)

[2] Ch. Engelmann et al.: Z. Phys. A352, 351 (1995)

[3] H. Geissel et al.: Nucl. Instr. Meth. B70, 286 (1992)

[4] M. Bernas et al.: Phys. Lett B331, 19 (1994)