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TRENDS IN THE RESEARCH PROGRAMME OF THE GSI FRAGMENT SEPARATOR *

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A selection of experiments performed at the Projectile Fragment Separator (FRS) in GSI in the last two years is presented with the focus on the presently reached limits for production of nuclei very far from the β-stability line.

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1. Introduction

In the last years, studies with radioactive beams evolved to one of the main streams of research in nuclear physics. On the world map of laboratories developing this technique, the GSI Darmstadt is distinguished by the broad range of secondary beams available and the unique conditions for their exploitation. The heavy ion synchrotron SIS [1] provides beams of all elements from protons to uranium with magnetic rigidity ($B\rho$) up to 18 Tm. Such a stable-isotope beam can be converted to a radioactive, secondary beam in a production target located at the entrance of the projectile fragment separator FRS [2] used for the subsequent in-flight separation. The secondary beam can be studied either at the different focal planes of the FRS, or can be injected into the storage ring ESR [3], or transferred to the external experimental areas in the target hall.

The status of the FRS facility and the description of some new experimental results with the focus on the precision measurements with radioactive ion beams injected into ESR has been recently given in Ref. [4]. An example of the experimental programme utilizing the combination of the FRS and ESR is also given in another contribution to this conference [5].

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In this report I shall concentrate on experiments performed at the final focus of the FRS. The aim of this survey is to present a selection of results obtained in the last two years illustrating present limits for the production of exotic nuclei very far from the β-stability line and some new techniques developed recently for the nuclear-structure studies.

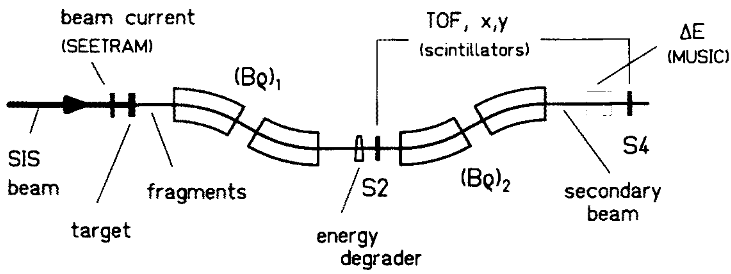

Fig. 1. Functional layout of the Projectile Fragment Separator and its standard detectors used for the in-flight identification.

The FRS is a zero-degree, two-stage magnetic spectrometer. In all examples described in the following it was operated in the standard achromatic mode [2]. A sketch of the FRS illustrating the basic principle of the in-flight ion selection and identification is given in Fig. 1. The primary beam of relativistic heavy ions from SIS impinges on a thick production target at the entrance of the spectrometer. The first stage of the FRS, comprizing two 30 degree dipole magnets, imposes an A/Z selection on projectile-like fragments which emerge from the target. In the dispersive focal plane in the middle of the separator an energy degrader can be inserted to impose an additional Z selection on the ions transmitted through the second magnetic stage (symmetric to the first one) to the final, achromatic focus. For the more detailed description of the FRS operation, reader is refered to Ref. [2].

Transmitted ions are identified in flight in the second stage of the FRS by the TOF–ΔE–$B\rho$ method using the standard detection set-up. Two plastic scintillators [6], located in the middle and the final focal planes, allow measurements of the time-of-flight (TOF) and positions in the horizontal (deflective) plane. Information on position, combined with precise measurement of magnetic fields, gives the magnetic rigidity ($B\rho$) of an ion. From TOF and $B\rho$ the mass over charge ratio A/Q can be deduced, which is equal to A/Z when ions are fully stripped. This condition was fulfilled in all discussed experiments. Energy loss of an ion (ΔE), characteristic of its nuclear charge Z, is measured in a four-stage ionization chamber (MUSIC) [7], located at the exit of the spectrometer.

2. Production of ^{78}Ni and other very n-rich nuclei by fission of ^{238}U

Fission of ^{238}U by a proton beam is known to be a very efficient reaction to produce n-rich isotopes of intermediate mass [8]. The possibility to accelerate uranium beam to relativistic energies and use of inverse kinematics opens a new way to investigate fission, which is induced by peripheral collisions with the target nuclei. This method takes advantage of the kinematic focusing of the fully stripped fission fragments, and possibility of their full identification by the $B\rho$–TOF–ΔE method in the FRS.

Two experiments, led by M. Bernas and P. Armbruster, were performed in GSI with a ^{238}U beam at 750 MeV/u energy; the first in 1992 and the second in 1995 with the average beam intensity being 2×10^5 and 10^7 uranium ions/s, respectively [9, 10]. In both runs two targets were used : 1 g/cm^2 beryllium and 1.25 g/cm^2 lead in order to disentangle the contributions of electromagnetic and nuclear interaction to the fission process. Within the angular and momentum acceptance of the FRS (30 mrad and 2%, respectively), only forward or backward emitted fission fragments can be transmitted. By tuning the separator to the longitudinal momentum larger than that of the projectile, forward emitted fission fragments are transmitted. Moreover, such a setting selects fragments originating from a low-energy fission of nuclei which evaporated either very few or no neutrons before fission ocurred, thus favouring n-rich isotopes having A/Z ratio close to that of ^{238}U.

In a series of different FRS settings the full kinematic range of fission fragments was scanned and charge distributions and fission yields for both targets were deduced [9]. The beryllium target was selected for the production of very n-rich nuclei in the Ni region, because the yield for asymmetric fission and luminosity was found larger than in case of lead target. The best condition for the transmission of ^{78}Ni was calculated to occur for magnetic rigidity of 16% larger than $B\rho$ of the primary beam. In the second experiment (1995) this setting was applied and during the collection lasting 132 h three events of ^{78}Ni were observed for the first time. The production cross section for this isotope was deduced to be 0.3(1) nb. In the same setting 56 other new n-rich isotopes of elements between titanium and niobium were observed. In total, both experiments resulted in the first observation of more than 100 isotopes, see Fig. 2, what constitutes a spectacular evidence that the low energy fission in inverse kinematics is a very promising tool for studies of very n-rich isotopes of intermediate mass. The increase of uranium beam intensity, planned in GSI in the near future, will allow decay-spectroscopy studies in this unexplored region what, hopefully, will bring a lot of interesting data for the nuclear-structure physics as well as

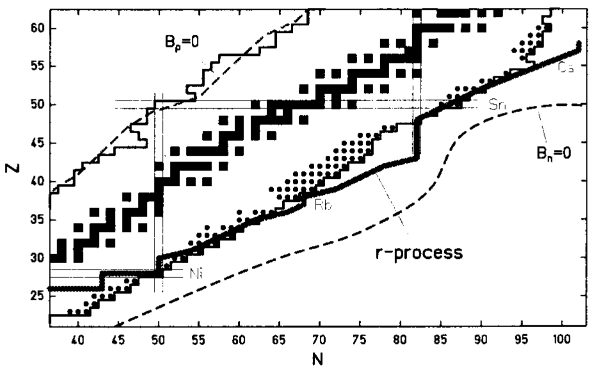

Fig. 2. Chart of nuclei with new isotopes observed in the fission of relativistic ^{238}U in the inversed kinematics. The predicted r-process limit [11] is indicated.

for nuclear astrophysics. In view of this latter aspect one should note that the nuclei lying on the r-process path are now accessible up to bromine and between tin and cesium.

3. Fragmentation of ^{58}Ni - towards ^{48}Ni

An exciting possibility exists that nickel, as the only element, has three doubly magic isotopes. While ^{78}Ni will be soon subject of spectroscopic studies which will inquire if this isotope is doubly magic indeed, the open question remains whether another candidate, ^{48}Ni is bound. The region of the very n-deficient nuclei around Ni, at the limit of stability, has another attractive feature — the best candidates for the yet unobserved phenomenon of 2p ground-state radioactivity are predicted to occur here. According to the recent calculation of Ormand [12] this new decay mode could be possibly observed in ^{39}Ti, ^{45}Fe and ^{48}Ni, with half-lifes $T_{1/2}^{2p}$ in the range 10 μs–3 s. Also ^{38}Ti was proposed as a possible candidate, however, its predicted $T_{1/2}^{2p}$ value of the order of 10^{-12} ms is too small in comparison with the time of flight through the separator (about 300 ns) to observe such a decay channel at the final focus of the FRS.

Exploration of this region was the main goal of an experiment performed at the FRS in the begining of 1996 by B. Blank and coworkers [13]. Very p-rich nuclei in the titanium-to-nickel region were produced by the fragmentation of the ^{58}Ni beam at 600 MeV/u on a 4 g/cm^2 beryllium target. To separate fragments of interest from the mass of less exotic contaminants, the aluminum degrader, of thickness between 1.8 g/cm^2 and 4 g/cm^2, was used at the intermediate focus. In the setting optimized for the transmis-

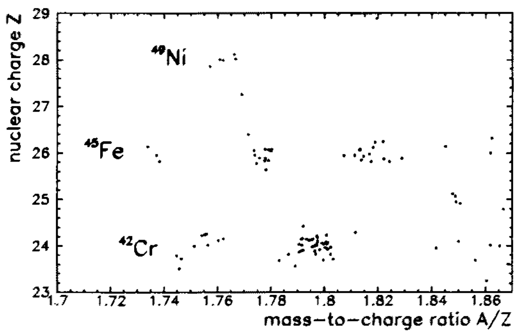

Fig. 3. Identification plot of nuclear charge Z versus mass-to-charge ratio A/Z showing the first observation of three new isotopes : ^{42}Cr, ^{45}Fe and ^{49}Ni.

sion of ^{45}Fe, after 72 h of counting with the average beam intensity of 10^9 ions/s, 3 new isotopes were identified : ^{49}Ni, ^{45}Fe and ^{42}Cr with 5, 3 and 10 events, respectively, as shown in Fig. 3. No counts were observed for ^{48}Ni as expected for this statistisc because the production cross section drops on average by a factor of 20 per mass unit in this region. One should stress, however, that both ^{45}Fe and ^{49}Ni, having $T_z = -7/2$, are the most proton-rich nuclei ever identified.

In another setting a search for ^{38}Ti was undertaken. After 24 h of data taking ^{39}Ti was observed with 166 events but no count could be assigned to ^{38}Ti. Taking into account the expected decrease in the production cross-section and slightly different transmission of ^{38}Ti and ^{39}Ti, one would expect 4–6 counts of ^{38}Ti. Unless the production cross section for ^{38}Ti is much smaller than assumed, the nonobservation of this isotope indicates that its half-life is short as compared to 300 ns flight time, in accordance with the prediction of Ormand [12].

It seems that from the theoretical and experimental point of view, ^{45}Fe is now the best candidate to search for the 2p decay. With the expected increase of the beam intensity the search for ^{48}Ni as well as spectroscopic studies of ^{45}Fe will be continued in the near future.

4. Fission of radioactive ion beams

With the fragmentation of a relativistic beam of ^{238}U at the FRS it is possible to produce secondary beams of more than 100 fissile nuclei which were previously unavailable for fission studies. In the interaction of such a secondary fissile beam with the heavy-Z target like lead, the electromagnetic excitation of the giant dipole resonance occurs with the large cross section of about 2.5 b. Therefore, even with low intensities of secondary beams one can perform detailed low-energy fission studies scanning the influence of the shell effects over a wide area of actinides.

An experimental programme aiming at that goal is being conducted in GSI by Clerc, Schmidt and coworkers [14]. The last experiment was performed in spring 1996. The fragments of interest were produced by fragmentation of 1 GeV/u ^{238}U beam on a 0.68 g/cm^2 beryllium target and separated by the FRS with use of the 3.8 g/cm^2 aluminum degrader. Behind the target and the degrader special niobium foils were mounted to maximize the amount of the fully stripped ions. At the final focus of the FRS, after the standard identification detectors, a setup dedicated to fission studies was installed. The secondary target was composed of lead foils of total thickness of 3.03 g/cm^2 mounted in a gas-filled ionization chamber, constructed in such a way that the lead foil in which a fission event occurred could be determined. This device allowed to discriminate against fission events induced in the materials upstream of the secondary target. The energy loss of the two fission fragments was measured by a double ionization chamber. Velocities of the fragments were determined by the time-of-flight method with the help of the scintillator wall (1m$\times$1m) mounted 5 m downstream of the secondary target. By combining the energy loss and the velocity data, the charges of both fission fragments could be determined.

The low-energy fission events were selected by a condition that the sum of charges of both fragments equals the charge of the fissioning nucleus. Next, the background due to high-energy nuclear induced fission was substracted by assuming that the charge distribution of fission in the plastic scintillator (in front of the lead target), in which no electromagnetic fission takes place, is the same as the distribution of the high-energy fission in lead. By this method the charge distributions in the electromagnetic-induced fission were obtained for more than 35 nuclei between ^{218}Ra and ^{234}U. One of the first results obtained was the observation of the graduate transition from the asymmetric distribution in ^{234}U, through triple-hump structure to the symmetric charge distribution in ^{223}Ac. More details on the experimental procedure and obtained results can be found in Refs. [15, 16].

5. Spin polarization in the fragmentation reaction at 500 MeV/u

At medium projectile energies spin polarization of projectile-like fragments was produced in peripheral heavy-ion collisions [17, 18]. At high projectile energies an alignment of the projectile spins was found [19]. The question, whether *polarization* can also be obtained in the relativistic energy domain was discussed in Ref. [20] and experimentally addressed at the GSI by W.-D. Schmidt-Ott, K. Asahi and coworkers.

In an experiment performed at the FRS at the end of 1995, a beam of 500 MeV/u ^{40}Ca was impinging on a 4 g/cm^2 beryllium target. ^{37}K fragments were separated and stopped at the final focus of FRS in a single KBr crystal in a static magnetic field of 0.5 T. The detection of spin polarization of ^{37}K was achieved by β-NMR. The asymmetry of the emitted decay positrons was measured using two scintillator stacks above and below the stopper. After implantation of ^{37}K the measurement was performed during the SIS-beam-off periods for spin positions up and down. The reversal of the ^{37}K spin direction was achieved by an RF field perpendicular to the static field and with a frequency matching the spin precession.

The spin polarization of ^{37}K was studied in dependence of kinematical conditions. By tilting the primary beam direction on the target one side of the transverse momentum distribution was selected by adjustment of the FRS entrance slits. Thereby positive and negative emission angles of the fragments could be achieved in consecutive measurements.

Preliminary values of the degree of polarization P are plotted in Fig. 4 versus the parallel momentum. A correction for the finite solid angle of positron detection will be added. In the upper and lower panel the data for positive and negative emission angles are shown, respectively. One can observe that the polarization has the same sign for all the parallel momentum intervals and reaches a maximum value of about 1% in the middle of the momentum distribution. Polarization changes sign when the emission angle is reversed.

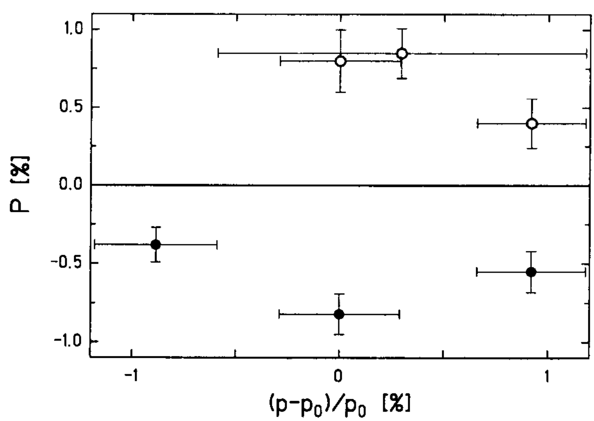

Fig. 4. Observed spin polarization of ^{37}K versus its parallel momentum. Upper and lower panel correspond to the positive and negative emission angle, respectively. The vertical bars denote the 1σ statistical error and the horizontal ones the accepted momentum interval.

The production of polarized secondary beams at relativistic energies can be applied to the measurement of magnetic properties of nuclei far from stability. A first attempt to measure the unknown g-factor of ^{35}K was undertaken.

6. Outlook

A possibility to reach experimentally exotic nuclei, very far from the β stability, like ^{78}Ni or ^{45}Fe, opens exciting perspectives for future studies of nuclear structure. Presently such studies are limited by the intensities of heavy-ion beams available at GSI. However, in the near future a substantial improvements are expected. Installation of an electron cooler at SIS, planned for 1997, will allow an increase of the beam intensities of all heavy ions by one to two orders of magnitude, so that the space-charge limit of SIS will be reached for ions up to nickel [21], see Fig. 5. Intensities of heavier beams will reach the space charge limit after replacing the Wideröe section of the UNILAC accelerator by the new high-current injector, which is planned for 1998 [21]. With final SIS intensities reaching 10^{11} ions per pulse, not only the decay spectroscopy of very exotic nuclei will proceed but also possibilities of secondary-reaction studies with radioactive beams, not limited to processes of large cross sections, will be substantially increased.

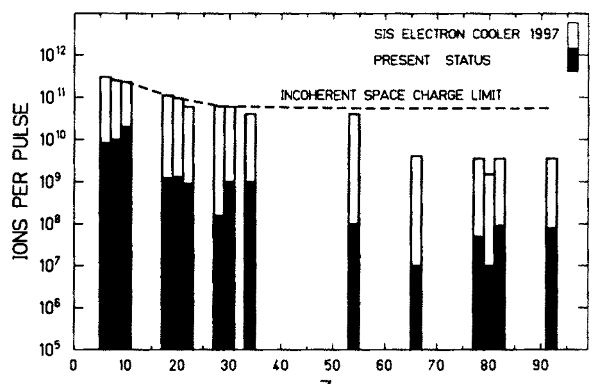

Fig. 5. Intensities of the heavy ion beams presently available at SIS, the planned increase due to the installation of electron cooler in the synchrotron and the final design goal given by the space-charge limit.

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REFERENCES

[1] K. Blasche, B. Franczak, *Proc. of the Third European Part. Acc. Conf.*, ed. H. Henke, H. Homeyer, Ch. Petit-Jean-Genaz, Gif-sur-Yvette: Editions Frontiere, 9 (1992).

[2] H. Geissel *et al., Nucl.Instrum. Methods* **B70**, 286 (1992).

[3] B. Franzke, *Nucl.Instrum. Methods* **B24/25**, 18 (1987).

[4] H. Geissel, Proc. IV Int.Conf. on Radioactive Nuclear Beams, Omiya, Japan, June 4-7, 1996, to be published.

[5] H.J. Kluge, contribution to this conference.

[6] B. Voss *et al., Nucl.Instrum. Methods* **A364**, 150 (1995).

[7] M. Pfützner *et al., Nucl.Instrum. Methods* **B86**, 213 (1994).

[8] J. Äystö *et al., Nucl.Phys.* **A515**, 365 (1990).

[9] M. Bernas *et al., Phys.Lett.* **B331**, 19 (1994) and P. Armbruster *et al., Z.Phys.* **A355**, 191 (1996).

[10] M. Bernas *et al.*, Proc. IV Int.Conf. on Radioactive Nuclear Beams, Omiya, Japan, June 4-7, 1996, to be published.

[11] P. Möller, K.L. Kratz, *ADNDT* **59**, (1995).

[12] E. Ormand, *Phys.Rev.* **C53**, 214 (1996).

[13] B. Blank *et al.*, accepted for publication in *Phys. Rev. Lett.*

[14] K.-H. Schmidt *et al., Phys. Lett.* **B325**, 313 (1994).

[15] A. Heinz, contribution to this conference.

[16] S. Steinhäuser *et al.*, Proc. Conference on dynamical aspects of nuclear fission, Casta-Papiernicka, Slovak Republic, August 30–September 4, 1996, to be published.

[17] K. Asahi *et al., Phys. Lett.* **B251**, 488 (1990).

[18] K. Matsuta *et al., Phys. Lett.* **B281**, 241 (1992).

[19] W.-D. Schmidt-Ott *et al., Z. Phys.* **A350**, 215 (1994).

[20] H. Okuno *et al., Phys. Lett.* **B335**, 29 (1994).

[21] D. Böhne *GSI Scientific Report 1995* **96-1**, 166 (1996).