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**EXPERIMENTS WITH RELATIVISTIC EXOTIC
NUCLEI AT THE FRS**

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EXPERIMENTS WITH RELATIVISTIC EXOTIC NUCLEI AT THE FRS

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ABSTRACT

The concept and experimental programme of the secondary nuclear beam facility BRENDA at GSI is presented. The central part of BRENDA is the magnetic spectrometer FRS providing spatially separated monoisotopic exotic beams of all elements up to uranium. The FRS as a versatile magnetic spectrometer for experiments with heavy ions in the energy range of (0.1 - 2) A · GeV has been used to study peripheral nuclear collisions from oxygen up to uranium projectiles. In the uranium experiments we discovered that projectile fission is a powerful tool to investigate new neutron-rich fission fragments. In the medium mass region we have identified the doubly magic nucleus ^{100}Sn and measured its half-life. Light halo nuclei have been studied in kinematically complete experiments with the FRS in combination with the dipole magnet ALADIN, and the neutron detector LAND. The FRS combined with the storage and cooler ring ESR offers new precision experiments, e.g., direct mass measurements, decay studies of highly-charged nuclei, or nuclear structure studies in inverse kinematics.

1. Introduction

Physics with secondary nuclear beams is a new rapidly growing field which is intimately tied to powerful accelerator facilities and the development of effective production and separation methods. Recent progress and novel developments are summarized in several review articles ^{1,2,3} and in the proceedings of international conferences ^{4,5,6,7,8}.

For the first time spatially separated relativistic exotic beams of all elements up to uranium can be provided for experiments and applications using the projectile fragment separator FRS ⁹ which is the main part of the new secondary beam facility BRENDA presented in the first section of this contribution.

In systematic studies of peripheral nuclear collisions we discovered that besides the widely applied fragmentation process projectile fission of relativistic ^{238}U is a promising tool to produce new neutron-rich nuclei ¹⁰. In-flight separation by mass and

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nuclear charge has been achieved with physical methods for both the light and the heavy fission fragments which is not possible at low energies due to atomic straggling. Some characteristic results of our investigations on peripheral nuclear collisions are briefly discussed in the 4th part of this article, a detailed description is given in Ref. ¹¹. Then we describe examples of nuclear structure studies using separated secondary beams. A kinematically complete experiment with light drip-line nuclei using the FRS in combination with the large dipole magnet ALADIN ¹² and the neutron detector LAND ¹³ is included, see also Ref. ¹⁴. Precision experiments with the combination of the FRS and the storage and cooler ring ESR ¹⁵ are illustrated in the following section.

2. The GSI secondary beam facility BRENDA

Nuclear studies far from stability are dependent on experimental facilities which produce and separate the nuclei of interest. Peripheral nuclear collisions ¹⁶ at high energies are well suited to produce exotic nuclei with velocities close to the projectiles. This favourable kinematics allows efficient separation in flight, a base to access nuclei down to half-lives in the sub- μ s range independent of the chemical element. The layout of the GSI facility BRENDA ¹⁷ is shown in fig.1.

Fig.1: Layout of the GSI secondary beam facility BRENDA.

The linear accelerator UNILAC injects the projectiles into the heavy-ion synchrotron SIS ¹⁸ at (11 - 15) A·MeV. The SIS provides beams of all elements from deuterium to uranium in the energy range from 50 to 2000 A·MeV. The maximum magnetic rigidity ($B\rho$) of the SIS is 18 Tm. Beams from SIS can be focused on a thick production target (several g/cm²) at the entrance of the FRS to convert the stable nuclei into exotic nuclear beams. These secondary beams can be investigated at the different focal planes of the FRS, or can be injected into the ESR, or directly

transferred to all facilities in the target hall, e.g., to the ALADIN magnet, the large neutron detector LAND, the KAOS spectrometer ¹⁹, or in the biophysics cave. Long-lived nuclei (nuclear life-time longer than the cooling time) cooled in the ESR to high phase-space densities can also be transferred to the external experimental areas. The ESR has a maximum magnetic rigidity of 10 Tm. The FRS branch direct to the target-hall facilities is presently under construction and will be commissioned in the beginning of 1995.

BRENDA is the only facility in the world providing both monoisotopic and fully-ionized exotic nuclei of all elements. In fig.2 we present a comparison of existing or planned exotic beam facilities characterized by their energy and element range of the fragments. The Coulomb barrier and the energies required to yield 90% fully-ionized beams after penetrating aluminium targets are plotted in the figure for orientation.

Fig.2: Comparison of existing and planned secondary beam facilities characterized by their energy and element range.

Fully-ionized fragments allow an unambiguous electromagnetic separation for each element, which is a necessary condition to provide a monoisotopic separation in flight with small background. Besides the energy and Z range a secondary beam facility is characterized by the rate of exotic nuclei, the separation time, and the amount of contamination. The rate is determined by the primary beam intensity, the target thickness, the production cross section, and finally by the separation efficiency.

In fig.3 we show the SIS intensities per pulse ¹⁸ presently available and the design goal, the incoherent space-charge limit which will be gradually reached by optimizations

of the ion sources and better phase-space matching for the SIS injection in combination with a new electron cooler that will allow repetitive multi-turn injection and successive electron cooling till the acceptance of $150 \pi \text{ mm mrad}$ is filled. With these developments the space-charge limit can be achieved for projectiles up to Xe whereas for the heavier ions this goal can only be reached with the planned high-current injector which will replace the Wideröe linac, the first part of UNILAC, by the end of 1998. The high-intensity SIS operation will provide $2 \cdot 10^{11}$ neon and $4 \cdot 10^{10}$ uranium ions per pulse. The target thicknesses at the FRS for fragmentation and fission reactions are $(1 - 9) \text{ g/cm}^2$ depending on the projectile and its energy. The separation efficiency is about 50% and can be higher for fragments with a small mass difference to projectile. The in-flight separation of less than $1 \mu\text{s}$ allows to study very short-lived nuclei. The luminosity range of BRENDA is presently $(10^7 - 10^9) \text{ b}^{-1} \text{ s}^{-1}$ and will be a factor 100 to 1000 higher for the heavier projectile fragments after the upgrade.

Fig.3: Projectile intensities of SIS per pulse ¹⁸ presently available, the improvements with a new electron cooler in the synchrotron, and the final design goal determined by the incoherent space-charge limit.

3. Spatial isotopic separation of relativistic exotic nuclei with the FRS

The FRS is a versatile magnetic forward spectrometer ⁹. For the separation and investigation of exotic nuclei the ion-optical system has been operated in an achromatic mode with the largest dispersion in the central focal plane. The $B\rho$ resolution and the longitudinal and transverse emittances have been adjusted to the experimental requirements by appropriate field settings of the quadrupoles. The FRS can alternatively be used as a high-resolution dispersive system whereby the $B\rho$ resolutions of the four dipole stages are added. This mode is particularly interesting for experiments using cooled beams.

Electromagnetic dissociation (ED), projectile fragmentation, and fission of heavy ions are the dominant nuclear reactions at relativistic energies for an efficient pro-

duction of secondary nuclear beams. In the following we will demonstrate that these reactions are rich sources for exotic nuclear beams. ED ²⁰ occurs at impact parameters larger than the sum of the radii of the two colliding nuclei. The relativistically contracted electromagnetic fields give rise to nuclear excitations. High-lying collective modes like the giant resonances can be excited with cross section in the barn range. The excited projectile nuclei decay via photon or nucleon emission, or, as in the case of very heavy beams, via fission. Except for the branch of induced fission, ED is a cold reaction process which produce final fragments close to the mass of the projectile. For heavy projectiles penetrating high-Z targets at an energy of several hundred A·MeV the contribution of ED to the total cross sections for the first neutron removal channels can even exceed the geometric cross section.

Fragmentation occurs at impact parameters where the radii of the interacting nuclei overlap. During the short nuclear encounter between projectile and target nuclei several nucleons are abraded. This collision creates a highly-excited prefragment which decays in the slower deexcitation step mainly via evaporation of nucleons. The hot fragmentation processes can provide nuclei far off stability. Fission can also occur in the deexcitation channel for very heavy prefragments.

These peripheral nuclear reactions are characterized by favourable kinematics for in-flight separation: The velocity of the fragments is close to that of the projectile and the parallel and longitudinal momentum distributions are narrow, i.e., the fragments are emitted in a small angular cone and narrow momentum band. These properties allow that the inflight and spatially separated fragment beams can be effectively transported to other dedicated ion-optical devices for further investigations.

Two experimental techniques have been used for the study of exotic nuclei at the FRS ⁹. The first method is the particle identification in flight by coincident magnetic rigidity and time-of-flight measurements in combination with the corresponding energy-deposition (Z determination) in an ionisation chamber ²¹. The ionisation chamber determines the charge of the fully stripped ions, i.e., these three observables identify the fragment by A and Z according to:

$$B\rho = \frac{A}{Z}\beta\gamma, \quad (1)$$

where β and γ are the velocity in units of the light velocity and the relativistic Lorentz factor, respectively. The second method ($B\rho$ - ΔE - $B\rho$) based on two-fold $B\rho$ analysis in combination with atomic energy-loss in (ΔE) specially shaped matter placed in a dispersive focal plane of the FRS provides spatially separated secondary beams of a single isotope.

An interesting example for the first experimental method is presented in fig.4 for the fission fragments created by 750 A·MeV ²³⁸U projectiles in a 1.2 g/cm² Pb target ¹⁰. We would like to note that this is the measurement where both light and heavy fission fragments have been separated in flight according to A and Z using physical methods. At lower energies the atomic energy straggling is a principal limitation to achieve this resolution ²².

In experiments with projectiles ranging from oxygen up to uranium we have successfully demonstrated that the FRS using the $B\rho\text{-}\Delta E\text{-}B\rho$ method is capable to perform a monoisotopic separation for fragments of all elements. For the most difficult case of U fragments the separation method was combined with TOF measurement to reduce the background due to the incomplete stripping ²³. The quality of the spatial separation for uranium projectile fragments can be seen in fig.5 presenting position measurements at the central and final focal planes. Using slits in both focal planes it is obvious that the selected isotopes can be completely separated.

Fig.4: In-flight identification of the fission fragments created by 750 A·MeV ²³⁸U projectiles in a 1.2 g/cm² Pb target ¹⁰. Z-distribution measured in an ionization chamber, on the left, corresponding mass distribution for a selected element, on the right.

The versatile ion-optical design of the FRS and the fact that all the magnets are connected to independent power supplies allow variations of the standard $B\rho\text{-}\Delta E\text{-}B\rho$ method, i.e., several combinations of energy degraders can be placed in each of the four focal planes. Such a set-up has the advantage that the resulting cascaded spatial separation reduces both the amount of transmitted contaminants from secondary reactions produced in the degrader itself and the count rate of non-selected ions for the detectors positioned at the following focal planes to provide in-flight particle identification. The shape of the degraders is prepared such that the achromatism of the ion-optical system is preserved if the priority in the experiment is the spatial separation. If the exotic nuclei are separated for implantation the shape of the degrader is adjusted to bunch the atomic range distribution ²⁴. In several experiments the degrader slope was chosen in between the achromatic and monoenergetic

mode to achieve both the optimum spatial separation and implantation adapted to the detector dimensions.

Fig.5: Spatial separation obtained for 950 A·MeV uranium projectile fragments. In this case the FRS was tuned on ^{236}U nuclei.

4. Studies of peripheral nuclear collisions

Studies of peripheral nuclear collisions at relativistic energies were pioneered at LBL ¹⁶ using mainly light projectiles up to Ca. Since the beginning of the operation of the FRS in 1991 we have extended the investigations on projectile fragmentation to heavier nuclei up to U. The goals were to improve the understanding of the reaction mechanisms, to produce new nuclei far of stability and to create beams for secondary-reaction experiments or applications as tracer beams.

We have measured formation cross sections and the reaction kinematics in the energy range from (100 to 1000) A·MeV. The experimental results are compared with refined abrasion-ablation models ²⁵, intranuclear cascade calculations combined with statistical evaporation codes ²⁶, and with the semiempirical EPAX formula ²⁷.

In fig. 6 our measured cross section for 500 A·MeV ^{86}Kr ²⁸ and 800 A·MeV ^{129}Xe ²⁹ fragments are compared with the different calculations. It is remarkable that the different descriptions of the fragmentation process reproduce the experimental data well. An illustration of the different reaction mechanisms induced by relativistic peripheral nuclear collisions is presented in fig.7. The measured cross section for 500 A·MeV ^{86}Kr , 1000 A·MeV ^{208}Pb , and 950 A·MeV ^{238}U fragments are compared with theoretical predictions ^{31,32}. The Kr fragments were produced in Be targets whereas the two heavier projectiles had nuclear collisions in Cu targets chosen to yield a higher electron-stripping efficiency. The selected cases include the three different reaction processes mentioned above: The Kr reaction products are a result of pure projectile fragmentation, for Pb, fragmentation determines the creation of most of the isotopes too except for the 1n and 2n removal channels. For these channels the ED process dominates the isotope formation. This statement is verified by the excellent agreement of the data with the theoretical description including both reaction mechanisms.

Our fragmentation data suggest that a mean excitation of 27 MeV per abraded nucleon yields the best agreement with the fragmentation predictions¹¹. In case of U fragments the influence of fission is clearly observed. The theoretical description can reproduce the data well if the fission probability is included in the projectile deexcitation. An empirical parametrization of the fission probability from ref.³⁰ was applied.

Fig.6 : Measured cross section for 500 A·MeV $^{86}\text{Kr}^{28}$ and 800 A·MeV $^{129}\text{Xe}^{29}$ fragments compared with a refined abrasion-ablation model (dotted line)²⁵, INC calculations (histogram)²⁶, and with the semiempirical EPAX formula (full line)²⁷.

The measured momentum distributions of the observed fragments reflect the intrinsic Fermi motion of the removed nucleons if the deexcitation phase, i.e., the nucleon evaporation has not the main influence. Only in rare cases where nucleons with extremely low binding energy are extracted, the momentum distribution of the final fragment is related to the wave function of the separated nucleons. This situation we find for light halo nuclei¹ discussed in the 5th section of this paper.

A criterium for the success of a production mechanism combined with the experimental separation method is the access to new nuclei far from stability. Nuclei with extreme proton-to-neutron ratio reveal the most interesting structure information and provide a crucial test for the models which are usually determined from stable isotopes.

Inspite of the relatively low intensity of the primary beam, we succeeded to discover many new isotopes. This was possible by the high selectivity and efficiency of the separation method. Two examples illustrate this statement. In fig. 8 projectile fission of 750 A·MeV ^{238}U was used to create neutron-rich nuclei. The experimental setup was already described in the 3rd section of this paper. In a run of less than 10 hours with a primary-beam intensity of about $10^5/\text{s}$ we produced more than 40 new

isotopes via fission in a 1.2 g/cm^2 Pb target, which are indicated in fig. 8 ¹⁰.

Another demonstration of the power of this new separation method achieved with the FRS is the discovery of extreme proton-rich nuclei in the mass region of $A \approx 100$. Much experimental and theoretical effort has been devoted to isotopes near the doubly-magic ^{100}Sn ³³ to verify the shell model predictions far from the line of β -stability.

Fig.7 : Measured cross sections for 500 A·MeV ^{86}Kr , 1000 A·MeV ^{208}Pb , and 950 A·MeV ^{238}U fragments compared with calculations ^{31,32} demonstrate the different reaction mechanisms induced by peripheral nuclear collisions at relativistic energies.

Fig.8 : Projectile fission of 750A·MeV ^{238}U was used to create neutron-rich nuclei. The full line marks the present limit of known isotopes ¹⁰.

The ^{100}Sn isotope however, could not be identified in the past with the applied reactions and separation tools. From our systematic fragmentation studies of $^{136,129}\text{Xe}^{34}$ projectiles we concluded that the doubly magic Sn nucleus could be produced via fragmentation of 1095 A·MeV ^{124}Xe in a 6 g/cm² Be target.

Fig.9 : First identification of ^{100}Sn ³⁵. Energy deposition in an ionization chamber plotted versus the mass-over-charge ratio.

Although the intensity of the primary beam was only about $3 \cdot 10^7/\text{s}$ we succeeded to observe ^{100}Sn for the first time ³⁵. The fragments were identified by combining the $B\rho\text{-}\Delta E\text{-}B\rho$ method with multiple time-of-flight and energy-deposition measurements. Furthermore, the spatially separated ions were implanted in a stack of silicon detectors for their identification by the range and for decay measurements. 7 events have been unambiguously attributed to the isotope ^{100}Sn produced with a cross section of about 5 pb. The separation quality is clearly demonstrated by fig. 9 showing the energy-deposition versus the calculated mass-over-charge ratio. Four ^{100}Sn events have been implanted in the same position-sensitive detector as predicted by our slowing-down calculations combined with the ion-optical imaging of the shaped degrader. The decay times of these ^{100}Sn nuclei were measured in correlation with the position information, a technique which was very successfully applied for the identification of the heaviest elements ($Z \geq 107$) ³⁶. Using the position correlation decay times compatible with the daughter ^{100}In and granddaughter ^{100}Cd nuclei were recorded. The preliminary half life of ^{100}Sn is $0.66^{+1.26}_{-0.44} \text{ s}$ ³⁷. ^{100}Sn has been also observed at GANIL by the reaction of 63 A·MeV $^{112}\text{Sn} + \text{Ni}$ ^{38,39}.

5. Nuclear structure studies with secondary beams

The production and separation of exotic nuclear beams at relativistic energies open a new field for nuclear structure studies by using inverse kinematics, e.g., elastic scattering and direct reactions applied for stable isotopes in the past can now be

performed for exotic nuclei. As an example, inelastic proton scattering to the first-excited 2^+ state of the doubly-magic ^{56}Ni nucleus was measured in inverse kinematics at the FRS ⁴⁰. The secondary beam of ^{56}Ni was obtained via fragmentation of 350 A·MeV ^{58}Ni in a 4 g/cm² Be target. The separation was achieved by using the $B\rho$ - ΔE - $B\rho$ method with an achromatic Al degrader which slowed-down the ^{56}Ni nuclei to an energy of 101 A·MeV before they interacted with a 1 mg/cm² (CH₂)_n target, placed at the final focal plane of the FRS. We measured the $B(E2, 0^+ \rightarrow 2^+)$ value and obtained $600 \pm 120 \text{ e}^2\text{fm}^4$ which is surprisingly high compared to the systematics in the literature for the doubly-magic nuclei of ^{16}O , $^{40,48}\text{Ca}$, ^{132}Sn , ^{208}Pb . However, the value is close to the neighbours ^{52}Cr , ^{54}Fe , ^{58}Ni and can be explained with modern shell-model calculations ⁴⁰.

Fig.10 : Measured differential cross section versus the four momentum transfer squared of $p^4\text{He}$ and $p^8\text{He}$ compared to calculations based on the Glauber multiple scattering theory with different density approximations ⁴².

Measurements of total nuclear interaction cross section of relativistic secondary beams led to the discovery of the halo structure by Tanihata et al. ¹. Another experimental method to determine the nuclear density distribution is elastic proton-nucleus scattering at relativistic energies. We launched an experiment to investigate the isotopes $^4,^6,^8\text{He}$ at 700 A·MeV ⁴². The secondary He beams produced by fragmentation of ^{18}O in Be were scattered in a hydrogen filled ionization chamber ⁴¹ used as an active target at the final focus of the FRS. The preliminary analysis of the data, see fig. 10, demonstrates clearly the neutron-skin structure in ^8He with rms radii of 1.67 fm and 3.2 fm for the ^4He core and the skin, respectively. Recently, the experiments on skin and halo matter distribution have been extended to heavier nuclei, e.g. $^{20-31}\text{Na}$ isotopes and A=20 nuclei produced via fragmentation of 1050 A·MeV $^{36,40}\text{Ar}$ projectiles. The analysis is still in progress.

Nuclear reaction studies in kinematically complete experiments contribute significantly to the understanding of the special nuclear-matter distribution characterized by very low binding energy of the outermost nucleons. In a combination of the FRS with the facilities LAND and ALADIN we have measured the fragment and the neutron distributions produced in break-up reactions of ^{14}Be , ^{11}Li , ^8He in light and heavy targets ¹⁴.

Fig.11 : Longitudinal and transverse momentum distributions of ^9Li after break-up reaction in a Pb target.

For the first time both longitudinal and transverse momentum distributions of the fragments have been measured at relativistic velocities. In experiments at the BEVALAC only the transversal component has been determined ¹. The longitudinal distribution is obtained by using the FRS as an energy-loss spectrometer. The transverse component is determined from angle measurements perpendicular to the dispersive direction at the ALADIN. Here we present results for the transverse and longitudinal momentum distributions of ^9Li created by break up of ^{11}Li in Al and Pb targets, see fig. 11. The measured width, 49 MeV/c, is narrow and agree for both momentum components. Furthermore, the widths of both target materials are the same within the experimental errors ⁴³ We have measured the longitudinal momentum distribution in the energy range from (280 to 650) A·MeV. The results show only a slight systematic energy dependence, i.e. with increasing energy the distribution becomes narrower. Results from measurements at MSU at low energy (66 A·MeV) are added for comparison ⁴⁴. It is striking that over this large energy range the longitudinal momentum width is almost constant which reflects clearly the low binding energy of the removed neutrons and the halo structure ^{11}Li , in accordance with the

results obtained by Kobayashi ⁴⁵.

Fig.12 : Widths (FWHM) of the longitudinal momentum distributions of 9Li after break-up reaction in a Pb target at different energies and in different target materials. Included are the corresponding experimental values obtained at much lower energy ⁴⁴.

6. Experiments with stored and cooled nuclear beams

Since the Fermi momentum of the removed nucleons and the deexcitation via evaporation have a small contribution to the total momentum of fragments, the emittances of relativistic secondary beams produced via peripheral nuclear collisions are relatively small. However, still for some investigations based on precise kinematical conditions the emittances of secondary beams must be improved.

The combination of the FRS with the storage-cooler ring ESR gives new perspectives for exotic-beam experiments:

- The high phase-space density ($\frac{\Delta p}{p} \leq 10^{-5}$ and transverse emittances of 0.1π mm mr) of cooled beams allows high-resolution experiments.
- The decay of bare or highly-ionized nuclei can be studied for the first time for all elements in the laboratory.
- Cooled secondary beams can be efficiently decelerated via the rf of the ring from relativistic velocities down to the Coulomb barrier.

Nuclear structure studies using direct reactions in inverse kinematics will also be continued with cooled beams. In-ring experiments are advantageous e.g.: a) for single nucleon transfer reactions $[(d,p), (p,d), (d,^3He)]$ which require deceleration of the separated exotic beam down to (10-15) A·MeV ⁴⁶, b) if a higher luminosity is achieved for stored exotic beams, or c) if the improved emittance obtained by cooling is necessary

to achieve the high resolution in the kinematical measurements.

The FRS-ESR system is well suited to perform direct mass and life-time measurements of stored exotic beams ⁴⁸. The relationship for the relative mass resolution $\frac{\Delta M}{M}$ using frequency measurements of the circulating beam is :

$$\frac{\Delta M}{M} = \gamma_{tr}^2 \left[\left(\frac{\Delta t}{t} \right)^2 + \left(1 - \frac{\gamma^2}{\gamma_{tr}^2} \right)^2 \left(\frac{\Delta v}{v} \right)^2 + \left(\frac{\Delta B}{B} \right)^2 \right]^{\frac{1}{2}} \quad (2)$$

From this equation it follows that the mass resolution is limited by the stability of the magnetic field of the storage ring $\frac{\Delta B}{B}$, the velocity spread $\frac{\Delta v}{v}$, and the accuracy for the revolution time $\frac{\Delta t}{t}$. γ and γ_{tr} are the relativistic Lorentz factor and the 'transition energy' characterizing the ion-optical tuning of the ring. The basic limitation for achieving a high-mass resolution is the inevitable velocity spread of the fragments. An experimental method to solve this problem is to apply electron cooling to reduce the velocity spread below 10^{-5} which has been already achieved in the ESR ⁴⁷. Another method based on tuning the ring on the condition ($\gamma = \gamma_{tr}$) is particular needed if short-lived nuclei are the goal of the mass determination.

Fig.13 : Schottky frequency spectra of cooled Ne fragments produced at 310 A·MeV in a 4 g/cm² Be target at the entrance of the FRS and stored and cooled in the ESR ⁴⁸. Decay of fully-ionized ¹⁸F.

An example of frequency spectra (Schottky scan) for cooled Ne fragments is shown in fig. 13 ⁴⁸. The FRS was operated in this case without degrader consequently a band of nuclei with the same $B\rho$ is injected into the ESR. After cooling of less than a minute the fragments have exactly the same velocity and therefore the different revolution frequencies reflect the mass-to-charge ratio to an accuracy of better than 10^{-5} . In the next experiments we will use this technique to measure masses in the

region of $A \simeq 200$. Nuclei which terminate the chain of α -emitters are of special interest since such investigations link the direct-mass determinations to the previously performed α -decay spectroscopy. The masses are particularly interesting because the ISOL techniques have difficulties to access this region and secondly the fragments are long-lived to apply the electron-cooling method.

Decay studies of few-electron and bare secondary nuclei are a unique feature of the FRS-ESR system. The first observation of bound-state β^- -decay ⁴⁹ of $^{163}_{86}\text{Dy}^{66+}$ has clearly demonstrated the possibility to study the influence of the atomic charge state on the weak interaction. As a consequence life-times of neutral and fully-ionized atoms can be drastically different, an observation which has also a strong impact on astrophysics. In a planned experiment this influence will be investigated for the decay of ^{56}Ni which will be produced by fragmentation of a ^{58}Ni primary beam in a Be target at the entrance of the FRS.

7. Summary

The results of the first experiments with the FRS demonstrate the new possibilities for physics with secondary beams at relativistic energies. The high quality of the separation method applicable for all elements allows to identify new isotopes with formation cross sections down to the pico-barn level as demonstrated in the discovery of ^{100}Sn .

Fragmentation and fission of relativistic heavy projectiles are a rich source for the production of new exotic nuclei which will be studied directly at the FRS or transported to the dedicated experimental areas like ALADIN, LAND, and KAOS.

Fission of relativistic projectile fragments induced by the Coulomb field of a heavy target nucleus extends the range of fissile nuclei for low-excitation fission studies from U down to the Pb shell ¹¹.

Studies of new neutron-rich nuclei in the heavy fission group and in the ^{78}Ni region are goals in future U experiments. A higher primary beam intensity can be expected since it has already improved by a factor 100 compared to the conditions we had during the described U experiment. In future experiments direct mass measurements and more elaborated spectroscopic studies of the new isotopes and their neighbours are planned. In this respect the Heidelberg crystal ball used for in-beam gamma spectroscopy of exotic nuclei will contribute to the planned investigations. The device will be placed in front of the ALADIN and LAND spectrometer.

The FRS operated as an energy spectrometer will be used to find new halo nuclei for both proton and neutron rich nuclei, e.g., ^8B is a promising candidate for p-rich light nuclei.

High-resolution measurements with the combination of the FRS and ESR will be continued intensively before the ring has a longer shut-down period in spring 1995 to install a new scattering chamber, the stochastic cooling facilities, and to perform the maintenance for the electron cooler which is presently limited in its maximum electron energy to about 200 keV.

Using cooled beams extracted from SIS make high-resolution experiments with the dispersive mode of the FRS very attractive. The multiphonon excitations of giant resonances might directly be observable in the energy-loss spectra of projectiles after penetrating heavy targets.

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