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Precision Experiments With Exotic Nuclei

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Progress and modern developments of secondary nuclear beam facilities based on the in-flight and ISOL separation methods are outlined. Precision experiments with nuclear beams characterized by large emittances have been performed by using special ion-optical conditions in spectrometers. A new generation of experiments have been started with stored and cooled exotic nuclei at sub-eV and at relativistic energies using the combination of an ISOL facility and an ion trap or the combination of an in-flight system with a storage and cooler ring, respectively. Both experimental scenarios are realized by ISOLDE and the ISOLTRAP at CERN and the fragment separator FRS in combination with the experimental storage ring ESR at GSI. The power and the potential of these devices are illustrated by direct mass and lifetime measurements.

Key words:

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1 Introduction

Recently, new secondary nuclear beam facilities have been commissioned or are in the construction phase, demonstrating the broad interest in studying exotic nuclei far from stability [1–3]. Special effort is devoted to experiments using radioactive nuclei at energies above the Coulomb barrier. This condition allows nuclear reaction experiments of the type which have only been possible with stable nuclei in the past. The merits of exotic nuclear beams at relativistic

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energies have been demonstrated with exciting new discoveries, e.g., nuclei with extreme isospins near the driplines form halo or skin nuclei characterized by a low matter density due to the large spatial extension of loosely bound valence nucleons [4,5].

When heavy ions penetrate matter the atomic charge-state distribution is determined by the kinetic energy of the incident beam, i.e., at energies of several 100 A·MeV, few-electron or bare ions can be created for all elements. This situation allows experiments under conditions which prevail in stellar plasma and therefore are relevant for basic astrophysical studies. For example, experiments with bare nuclei led to the discovery of beta decay into bound states [6,7]. The results extend the knowledge on beta decay and contribute to a precise calibration of the ^{187}Re - ^{187}Os galactic chronometer.

In general, small longitudinal and transverse emittances and a long observation time (>1 s) are decisive parameters for precision measurements. However, the stochastic processes of the atomic and nuclear collisions during penetration through matter enlarge the emittance of the primary beam such that subsequent high-resolution experiments require special techniques. By selecting specific ion-optical conditions, as used for the operation of an energy-loss spectrometer or for an isochronous time-of-flight system, one can circumvent the influence of an enlarged incident beam emittance. Unique possibilities are opened by the storage and cooling facilities in traps and storage rings. The application of ion traps and heavy ion storage rings in the field of electromagnetic isotope separation is a promising novel development and is a main subject of this contribution.

2 Production and separation of exotic nuclei

Exotic nuclei are produced in central and peripheral nuclear collisions over a wide range of projectile energies. The reaction kinematics determines if the produced nuclei can be separated in flight and used directly for secondary nuclear reactions or if they have to be post-accelerated.

At high energies, above the Fermi domain, only the overlapping zone of the colliding nuclei participates in the nuclear interaction. The heavy residues outside this region, the spectators, represent a rich source for exotic nuclei. This nuclear fragmentation process is an efficient reaction mechanism to produce radioactive nuclei over the entire periodic table up to the heaviest available targets and beams. In secondary beam facilities the fragmentation is induced either by heavy ions or protons depending on whether target fragments or projectile fragments are used.

Fig. 1. In-flight identified fragments created by fission of 750 A·MeV ^{238}U projectiles in a lead target. The magnetic rigidity ($B\rho$) of the fission fragments in this measurement was selected to be 4 % higher than the corresponding $B\rho$ of the projectiles emerging from the target [8]. β and γ are velocity (v/c) and the relativistic Lorentz factor, respectively.

Neutron rich exotic nuclei can be produced efficiently by fission induced by neutrons, energetic protons, or heavy ions. Recently, fission of relativistic projectiles in flight, such as 750 A·MeV ^{238}U in a heavy target (Pb), has opened up new possibilities [8]. In this reaction the heavy target interacts via the Lorentz-contracted Coulomb field and excites the giant resonances in the projectile nucleus. The highly excited projectile mainly decays by nucleon emission or fission. In the first experiments employing projectile fission 108, new neutron-rich reaction products have been created, including the doubly magic nucleus ^{78}Ni [9]. Relativistic fission fragments are experimentally very favourable since their in-flight identification can be performed with high resolution due to the characteristics of the atomic interactions in this energy range [10]. At low energies, in the 1 A·MeV regime, the atomic straggling effects in matter limit the Z-resolution in ionization detectors to the light fission group, whereas single elements in the heavy group cannot be resolved in contrast to the situation at relativistic energies. An example of the good resolving power of the particle identification in mass and element number over the full Z-range of fission fragments is illustrated in figure 1.

More than 30 isotopes for one selected element can be provided by employing fragmentation and projectile fission at relativistic energies at the fragment

Device	Projectile	Energy MeV/u	Intensity	Reaction	Target
Reactor	Neutrons	thermal	$10^{15}\text{cm}^{-2}\text{s}^{-1}$	FI	(1-10) g ^{235}U
LINAC	Neutrons	100	10^{15}s^{-1}	FR, FI	$> 100\text{ g/cm}^2$ U, La
LINAC	Protons	10 -100	10^{13}s^{-1}	FI	0.1 g/cm 2
Cyclotron		10 -500	$6\cdot 10^{15}\text{s}^{-1}$	FR	2 g/cm 2
Synchrotron		100 -1000	10^{15}s^{-1}	FR	(50-100) g/cm 2
LINAC	Heavy Ions	1 -20	10^{13}s^{-1}	FU, TR	(0.1-1) mg/cm 2
Cyclotron		20 -100	10^{13}s^{-1}	FR	(0.1- 0.4) g/cm 2
Synchrotron		100 -2000	10^{11}s^{-1}	FR, FI	(1-8) g/cm 2

Table 1

Production of exotic nuclei in different reactions and energy domains. The energy ranges determine the projectile sources and the maximum intensities. The applied nuclear reactions are fission (FI), fragmentation (FR), fusion (FU) and transfer (TR).

separator FRS [11]. Similar results can be reached by target fragmentation and fission induced by 600-1000 MeV protons using lanthanum and uranium targets at ISOLDE [12].

The intensity of secondary beams depends on the production cross section, the projectile intensity, the target thickness, and the separation efficiency. Different production reactions, energy regions, and projectile sources have various operation domains as summarized in table 1. Under optimized conditions one can reach rates of secondary nuclear beams which are only a factor of 10^{-4} - 10^{-3} less than the primary beam if the selected nuclei are not too far from the valley of stability.

Decisive for the intensity of secondary beams is the applied separation method. The two main separation techniques are the ISOL and the in-flight method [3,12-14]. A schematic comparison of both separation scenarios including the recent developments is presented in fig. 2.

In general ISOL devices use thick production targets and catchers where the projectile beam is fully stopped (see table 1). In this facility the reaction products are thermalized and then transported by diffusion processes from the target or catcher to an ion source for ionization before they are accelerated to the typical levels of 10-100 keV. Electromagnetic fields separate the nuclei according to their mass-to-charge ratio.

The higher intensity of proton accelerators compared to heavy ion accelerators and the thicker production target represent advantages for the ISOL facilities,

SEPARATION METHOD

Fig. 2. Principles of modern secondary beam facilities based on the ISOL and in-flight production and separation methods. The separation time and the energy range after the electromagnetic separation stage are the characteristic differences of the methods.

i.e. they have higher yields of reaction products for their developed secondary beams. However, the ISOL technique is limited to lifetimes in the order of 10 ms dependent on the chemical and solid-state characteristics of the reaction products, which determine the speed of the diffusion and effusion processes.

In-flight devices take advantage of specific reaction kinematics to separate nuclear reaction products from contaminants with a high suppression factor. Because the target is much thinner than in an ISOL facility, the reaction products penetrate the ion-optical system with high velocities. A combination of electric and magnetic fields is applied in in-flight separators up to medium energies, whereas at relativistic energies mainly magnetic fields are applied for technical reasons. A major advantage of an in-flight separator is that the half-life limits for the separated secondary beam are only determined by the time-of-flight through the ion-optical system, which is on the order of microseconds

in devices used near the Coulomb barrier and a few hundred nanoseconds in separators for relativistic nuclei.

New domains far off β -stability have been successfully explored with the ISOL and in-flight separators. The dimension of this research can now be expanded by the possibility to provide the separated secondary beams with energies exceeding the Coulomb barrier allowing nuclear reaction studies with exotic projectiles. This goal can be achieved with the ISOL facility if the device is coupled via a second ion source to a post-accelerator system [15] (fig. 2). The in-flight separators based on projectile-fragmentation kinematics directly provide exotic beams well suited for secondary nuclear reaction studies. For the first time spatially separated monoisotopic relativistic beams of all elements up to uranium have been provided with the projectile fragment separator FRS [11,16].

New precision measurements become possible if an in-flight system operated at relativistic energies is combined with a storage-cooler ring or an ISOL facility with a Penning trap system (fig. 2). The storage-ring system for heavy ions can be extended with a collider ring with electrons to investigate the nuclear structure by electron scattering experiments. Such developments were first proposed for the radioactive beam facility in Dubna and more recently also for the upgrades at RIKEN [17] and at GSI [18].

3 Precision experiments with exotic nuclear beams at large emittances

Precision experiments based on kinematical observables of energetic ions are difficult with incident beams characterized by large emittances. The stochastic processes in the formation of nuclear reaction products and the atomic collisions in the target normally result in drastically enlarged emittances compared with the primary projectile beam. Therefore, special methods are required if a radioactive beam, separated in flight, is to be used for precise kinematical measurements.

In a few cases the problem can be solved by the application of coincidence measurements before and after the secondary reaction target. However, the maximum count rate and the atomic straggling effects in the active detector material can severely restrict such a method. A better solution is provided by the use of special ion-optical instruments, which cancel in their final image conditions the influence of the kinematical spread of the incident beams.

In this respect, an elegant solution is to use an energy-loss spectrometer. Such a device consists of two dispersive ion-optical stages. The first stage is called

analyzer and the second one spectrometer. Both stages are characterized by the same value of the magnetic-rigidity ($B\rho$) resolution but acting in opposite directions, i.e., the dispersions have to fulfill in first-order optics the following relation:

$$(x, \delta)_2 = -(x, x)_2 (x, \delta)_1 \quad (1)$$

where $(x, \delta)_2$ and $(x, x)_2$ represent the matrix elements for dispersion and magnification of the spectrometer stages 1 and 2 (indicated by subscripts), and $(x, \delta)_1$ the corresponding dispersion of the analyzer stage.

In the following, two examples of recent applications of an energy-loss spectrometer with relativistic heavy ions in the velocity range $0.4 \leq v/c \leq 0.9$ are presented. The first kind of experiments investigates the ion penetration through matter at velocities where the projectiles are bare or carry only few electrons. Accurate knowledge of the atomic penetration phenomena for relativistic ions in matter is essential for the spatial separation of monoisotopic nuclear beams [16]. In the second example nuclear structure studies are performed with halo nuclei characterized by a large emittance due to their production process.

Using the FRS as an energy-loss spectrometer precise atomic collision studies [19,20] have been performed with few-electron ions up to uranium. The accuracy of the momentum determination in these experiments was better than 10^{-4} . The data demonstrate systematic deviations from relativistic calculations based on the first Born approximation, such as the Bethe stopping power theory. The measured heavy ion stopping powers are up to about 10 % larger than the values predicted by the Bethe theory, whereas the data for energy-loss straggling exceed the corresponding theory for the heaviest ions by up to a factor of 2.5. A new theoretical approach is in excellent agreement with the precise experimental results [19,21,20]. More details on these experiments combined with the isotopic separation of secondary beams are presented at this conference by Iwasa et al. [22].

An energy-loss spectrometer is an ideal tool to study the break-up reactions of relativistic halo nuclei. Halo nuclei consist of a core surrounded by loosely bound valence nucleons. The measured momentum distribution of the core fragments yield information on the structure of these nuclei determined by the valence nucleons which form a low-density nuclear matter distribution with a comparatively huge spatial extension [4]. Such momentum distributions of core fragments from halo nuclei have been measured at medium energies (40-80 A·MeV) with the A1200 [23] and at higher energies (300-1500 A·MeV) with the FRS, both magnetic devices were operated in the energy-loss mode.

For the interpretation of the results it is necessary to deduce the influence

of the selected reaction process on the measured distribution before conclusive statements on the wave function of the loosely bound halo nucleons can be made [24,25]. Break-up reactions at several hundred A·MeV can be well analyzed in the eikonal approximation and the longitudinal momentum distribution is particularly well suited to study the halo nuclei. Experimental results on the one-nucleon halo nucleus ^{11}Be show two striking features [26,27]. The measured widths (fwhm) of the longitudinal momentum distribution of ^{10}Be after break-up reaction of ^{11}Be are within 10 % constant (fwhm = 45 MeV/c) in the large energy region from 60 to 680 A·MeV in different target materials (Be to U) and further the magnitude of the width is about a factor 5 smaller than the corresponding width for nuclei characterized by tightly bound nucleons. Both experimental results suggest that the data directly reflect the particular nuclear structure of the investigated nuclei. Narrow resonances and final-state interactions should not obscure the interpretation for the ^{11}Be nucleus. Therefore, the calculated wave function for the loosely bound (504 keV) valence neutron using QRPA theory [28] yield good agreement with the measured momentum distribution. The measured momentum distribution of ^{10}Be after removal of the valence neutron in ^{11}Be is presented in figure 3 compared with the theoretical prediction, folded with the transmission of the FRS for a fixed setting of the magnetic fields at the center of the distribution. Details will be discussed in a forthcoming publication [27].

Fig. 3. Momentum distribution (projectile frame) of the ^{10}Be nuclei after removal of the valence neutron from ^{11}Be at 666 A·MeV in aluminum. The experimental result is represented by the histogram. The dashed line represents the theory using QRPA methods [28] whereas the full line is the QRPA calculation folded with the experimental transmission.

Besides laterally dispersive ion-optical systems, longitudinally dispersive spectrometers can be used to perform high-resolution measurements with nuclear reaction products characterized by a large emittance. A time-of-flight system uses, for example, the isochronous condition that the flight-time through the ion-optical system is only dependent on the mass-to-charge ratio but not on the velocity. This means the faster ions of the same isotope are guided to travel through the spectrometer on a detour. The longer path is exactly matched to the larger velocity with respect to the reference particle which is transmitted on the optical axis. Such systems, like the TOFI spectrometer at LAMPF [29], the isochronous cyclotrons [30], and storage rings, like the ESR [31,32], are well suited for precise direct mass measurements independent on the large emittance of the nuclear reaction products.

Recent mass measurement of very proton-rich secondary ions in the region of $A=100$, including the doubly magic nucleus ^{100}Sn , using the isochronous conditions in the CSS2 cyclotron at GANIL, have demonstrated the power of such longitudinal dispersive systems [30]. A similar experimental technique has been applied by using the cyclotron SARA for mass measurements of $A=80$ isobars [33]. The isochronous operation mode of the storage ring ESR is presently under development. First results with $370\text{ A}\cdot\text{MeV Ca}^{20+}$ ions demonstrate that a spread for the measured revolution frequency of $\Delta f/f = 2 \cdot 10^{-6}$ can be obtained for stored beams [34] independent of the corresponding momentum spread. Presently, the lower limit of frequency spread is caused by the variations of the magnetic fields [35]. A major advantage of the isochronous time-of-flight systems is that the method allows access to very short-lived ions down to the lower limit determined by the time-of-flight through the optical device.

4 Precision experiments with stored and cooled beams

Cooling and storage of exotic nuclei in ion traps and storage rings are one of the most fascinating modern developments. The large emittances of nuclear reaction products can be drastically reduced by various cooling techniques to achieve conditions suited for high-precision measurements. The drawback is that the time needed for the ion preparation and for the cooling process sets a limitation for the application to short-lived exotic nuclei. Nuclei with lifetimes on the order of seconds represent the lower limits if electron cooling is applied in a storage ring. The electron cooling time is strongly dependent on the incident velocity spread, therefore stochastic precooling can reduce the overall cooling time. A versatile tool particularly well suited for the cooling of heavy ions in a trap is the mass selective buffer gas cooling technique [36,37], where cooling times in the order of 10 ms can be achieved.

Ion traps [38] confine the motion of charged particles to a very small volume under ultra-high vacuum conditions and allow in this way a long observation time without suffering from perturbations by the material of the surrounding experimental setup. Confinement and precise control of the motion of the trapped ions are achieved via application of static and radio-frequency electromagnetic fields to special electrode structures of the traps in combination with cooling techniques. The storage and long observation time of a few or even a single particle trapped in a very small volume ($< 1 \text{ mm}^3$) make the ion trap to one of the most precise instruments in physics [39]. The most commonly used types of electro-magnetic traps are the Penning and the Paul trap. The Penning trap is particularly well suited as a high precision mass spectrometer. Its electrode structure, placed in a strong homogenous magnetic field, provides a weak electrostatic quadrupole potential, which leads to an axial confinement of the ions. Due to the presence of this electric field the ion motion in the plane perpendicular to the magnetic field axis is composed of the slightly modified cyclotron motion and a drift motion around the trap axis. From the characteristic frequencies of these motions the cyclotron frequency

$$\omega_c = \frac{q B}{m} \quad (2)$$

of an ion with a charge-to-mass ratio q/m stored in a magnetic field of strength B can be determined. The mass of the ion with known charge state can be obtained from ω_c after calibration of the magnetic field. This is achieved via a cyclotron frequency measurement of an ion of known mass (preferably ^{12}C). For accurate mass measurements cooling of the trapped ions is important in order to keep the amplitudes of the ion motion as small as possible and thus minimize systematic effects caused by residual imperfections in the electric and magnetic trapping fields.

The great success of the ion traps in particle physics and other fields make it obvious to introduce the devices for precision experiments with radioactive beams. Presently, only the ISOLTRAP tandem Penning trap system at ISOLDE/CERN [40] is operated as a mass spectrometer for exotic nuclei.

The ISOLTRAP set-up consists of two Penning traps following an ion preparation section (see fig. 4). The first trap serves as ion accumulator, cooler and buncher, the second trap as mass spectrometer. The continuous 60 keV ISOLDE beam has been collected on a filament of a secondary ion source system which is heated to release and surface ionize the accumulated ions. From the ion preparation section ions are delivered with a kinetic energy of approximately 1 keV and transported by an ion-optical transfer system to the first Penning trap. After retardation to the eV range, they enter the first Penning trap [41] where their accumulation is assisted by a buffer gas. Recently, this first trap has been substantially improved in efficiency and resolution [42]. It

Fig. 4. ISOLTRAP and the FRS-ESR facilities for precise mass measurements of exotic nuclei. The kinetic energies of the stored ions and the size of the storage volume are the main differences. The closed orbit of ions stored in the ESR has a circumference of 108.4 m whereas the corresponding volume in the trap is less than 1 cm^3 . In the trap system the ions are cooled in a helium buffer gas whereas the phase space of the circulating ions in the ESR is reduced by electron cooling.

has a cylindrical electrode structure for efficient accumulation and is placed in the homogeneous dipole field of a 4 T superconducting magnet. The ions are cooled to room temperature by collisions with He atoms at about 10^{-4} mbar. The energy loss decreases the axial and cyclotron amplitudes whereas the magnetron oscillations are increased. The latter process is counteracted by rf excitation of the ω_c resonance for a selected ion species. In this way the first Penning trap prepares cooled ion bunches of a single isotope. A mass resolving power of about 100000 is achieved which is sufficient to separate isobars. The pure ion bunches are then transferred into the precision trap. This trap has hyperbolic electrodes and is placed in the homogenous field of a 6 T superconducting magnet. Here the precise determination of the cyclotron frequency takes place. It is determined via radiofrequency excitation of the motion of the trapped ions which are then extracted from the homogeneous field and detected by a detector placed at 1.3 m distance from the trap. Along this drift length through the inhomogeneous part of the magnetic field the energy gained by the rf excitation inside the trap is converted into longitudinal en-

ergy. The measured time-of-flight as a function of the applied radio frequency yields a resonance curve with a minimum at the cyclotron frequency of the ion under investigation. The line width $\Delta\nu(fwhm) \approx 1/T_{rf}$ of the resonances is Fourier-limited and given by the excitation time T_{rf} . For heavy ions $A \approx 100$ resolving powers up to 10 million have been obtained by using excitation times up to 10 s.

The operation of the ISOLTRAP has shown that a high mass resolving power of the first Penning trap is essential to remove contaminants from the beam before the cyclotron frequency is measured in the precision trap. Stored ions contaminated by other masses cause severe frequency shifts in the observed resonances, proportional to the number of stored contaminants [43]. Coulomb interactions of identical ions result in practically no systematic effects and for beam time economics it is found to be very useful to use up to several tens of ion stored simultaneously in the trap.

With the ISOLTRAP system mass measurements have so far been carried out on more than 100 radioactive isotopes of surface ionizable elements [44–47]. An accuracy of $1 \cdot 10^{-7}$ has been achieved for all investigated isotopes. Recently, the first stage of ISOLTRAP, the secondary ion source, has been replaced by a Paul trap which can retard and accumulate the ISOLDE beam in flight. This device removes the dependence on the surface-ionization and extends the available ions for mass measurements with similar accuracy to the full element range of ISOLDE.

Mass measurements via frequency spectroscopy of exotic nuclei in a completely different range of kinetic energies have been performed with the FRS-ESR. Relativistic fragments have been produced and separated in flight with the FRS. The separated reaction products are injected at about 350 A·MeV into the storage ring ESR [31,49] where the phase space of the ions is reduced by electron cooling. The interaction of the nuclear beam with the coaxially merged electron beams forces all the stored ions to the same mean velocity determined by the selected kinetic energy of the electrons and reduces the momentum spread to approximately 10^{-6} . At 350 A·MeV light and medium projectile fragments are bare and only the heaviest elements have a small population of H- and He-like states. Ultra-high vacuum conditions ($< 5 \cdot 10^{-11}$ mbar) and the electron cooling force allow ions to be stored up to many hours in this large (108.4 m circumference) trap. The masses of the cooled circulating ions are determined via precise measurements of the revolution frequency which is proportional to the mass-to-charge ratio. The absolute calibration is obtained by the frequency determination of several well known masses in the frequency range of the unknown masses. The frequency spectroscopy is performed with Schottky analysis using non-destructive pick-up probes. The circulating ions induce current signals which are analysed by fast Fourier transformation. As with the Penning trap it is necessary to reduce the number of

stored ions to achieve the highest possible resolution. Systematic measurements with electron cooled bare ions have shown that the momentum spread is drastically reduced and reaches a constant value if the number of stored ions is less than several thousand [35]. These observations can be explained by a drastic reduction of the intrabeam scattering and suggest a phase transition of the stored ions. The results demonstrate that frequency measurements with maximum resolution can be performed for cooled ions at low intensity. This condition represents no restriction for the mass measurements since only ions close to stability are available with high intensities. On the other hand, the Coulomb interaction of ions in the storage ring should have less influence on an accurate mass determination, compared to the sensitivity due to higher particle density in the trap.

Fig. 5. Part of the Schottky frequency spectra for cooled 200 A·MeV nickel fragments with $A/Z = \frac{2Z+1}{Z}$. The accuracy of the mass determination in this mass range is about 25 keV and the resolution about $4 \cdot 10^{-6}$.

Since the first storage and cooling of secondary heavy-ion beams [50] much progress has been achieved for the cooling performance [35] and Schottky analysis [49] of the circulating beams in the ESR. For a low-intensity stored and cooled secondary beam of ^{58}Ni fragments at 200 A·MeV the measured momentum spread was about $5 \cdot 10^{-7}$ [51]. In principle, the momentum spread can be still smaller based on the temperature of the electron beam, however, the stability and uniformity of the magnets determine the present lower limit [35] (see section 3). An example of a measured Schottky frequency spectrum for nuclei produced by ^{58}Ni projectiles is illustrated in fig. 5. The ions with similar mass-to-charge ratio $A/Z = \frac{2Z+1}{Z}$ are well resolved and even on this coarse overview spectrum the separation of the ground and isomeric states of ^{53}Fe is visible. The identification and separation of isomeric states are needed

for high resolution mass spectroscopy.

The ground and isomeric states in ^{53}Fe are separated by 3.04 MeV. A greater challenge is to resolve the states in ^{52}Mn where the ground and isomeric states are only separated by 378 keV. The corresponding Schottky frequency spectrum for ^{52}Mn is presented in fig. 6 together with a mass distribution measured with ISOLTRAP for ^{141}Sm . The spectra demonstrate clearly the excellent resolving power of both experiments. Presently, the ISOLTRAP has a higher resolution whereas the FRS-ESR system has advantages in systematic mapping of a large part of the mass surface. A combination of both experiments could be fruitful: with the trap some precisely determined reference masses can be provided in a territory of unknown masses and the FRS-ESR system can then map a large mass region, particularly in regions where ISOLDE has difficulties providing the separated nuclei.

Fig. 6. Mass spectra demonstrating the high resolving power of both the ISOLTRAP and the FRS-ESR facilities. The ground and isomeric states of ^{52}Mn and ^{141}Sm are well resolved in both experiments.

In the Schottky spectra the conditions can be chosen easily such that many reference masses are incorporated in one spectrum together with new masses to be determined. This feature was demonstrated with mass spectra obtained for proton-rich bismuth fragments [52]. The calibration procedure was in this experiment extended by the charge-state population of the fragments, i.e., each nuclear mass was measured in up to 3 atomic charge states (bare, H-like, He-like). In fig. 7 this feature is illustrated by mass measurements of ^{184}Pt in different charge-states and with respect to different reference masses. In this experiment about 110 masses were measured for the first time and about the same amount of new masses could be determined additionally by combining the data obtained by Schottky spectroscopy with Q_α values from the literature [52].

Fig. 7. Mass determination for ^{184}Pt in different ionic charge states and with respect to many different reference masses. The mean value with the band of one standard deviation (σ) is indicated.

In the mass region of $A = 200$ an accuracy of about 100 keV was obtained. It is noteworthy that the accuracy of the FRS-ESR system has not yet reached the full potential, for example in the next measurements the mass spectra will be accumulated with their time correlation. This method will allow corrections for drifts and instabilities of the storage ring facilities, like the power supplies for the magnets or the terminal voltage of the electron cooler. The experimental masses for Pb and Cs are obtained from FRS-ESR and ISOLTRAP measurements, respectively and from the compilation of Audi and Wapstra [54]. The new data can contribute to a better understanding of the mass description as illustrated in a comparison with different theoretical predictions. Measured masses for Cs and Pb isotopes are compared to different theoretical models [53,58] indicated in fig. 8. For illustration fully microscopic Hartree-Fock-Bogolubov approach with the different forces, e.g., zero-range effective Skyrme (SkP parameterization) and finite-range Gogny forces for Pb isotopes has been used. As example of another microscopic approach the Extended Thomas-Fermi with Strutinski Integral (ETFSI) has been presented for both Cs and Pb isotopes. The data are compared also with the Macroscopic-Microscopic (Finite Range Droplet Model-FRDM) [57] method. Thomas-Fermi predictions

Fig. 8. Measured masses for isotopes of Cs and Pb compared with theoretical predictions. The microscopic models based on self-consistent Hatree-Fock-Bogolubov are indicated by the different forces used, e.g., Skyrme force (SkP, dashed line) and Gogny force (dashed-dotted line). The Macroscopic-Microscopic (FRDM, dotted line) approach, and the Extended Thomas-Fermi model with Strutinski Integral (ETFSI, full line) are also included. The experimental data for Cs and Pb (full squares) are obtained at the ISOLTRAP and FRS-ESR facilities, respectively, and the full circles represent the data from the compilation of reference [54].

were used as a reference in the comparison[56]. For illustration only isotopes with even number of neutrons have been selected. Although FRDM and ETFSI models give presently the better description for the experimental results than the HFB (Hatree-Fock-Bogolubov) calculations, the improvements, using new

measured experimental data, of these self-consistent theories can give a better insight into the nucleon-nucleon interactions. The study of pairing effects near driplines can be especially interesting. The figures 8 demonstrate that the present experiments need to be extended towards the driplines to be decisive for the accuracy of the theoretical predictions in this region.

Nuclides with shorter half-lives can be reached in the future by using the isochronous ion-optical mode of the ESR [59], or an on-line radio frequency spectrometer at ISOLDE [60].

Mass and decay measurements belong to the fundamental investigations of atomic nuclei. Spectroscopy at relativistic energies allows for the first time nuclear studies as a function of the atomic charge states. A programme of decay studies of bare and few-electron radioactive heavy ions have been started with the FRS-ESR facility. Half-lives can be measured via the decreasing intensity of the stored mother nuclei or by directly detecting the daughter nuclides. There are three options for the latter case: 1) the magnetic rigidity change of the decay is within the 2.5 % acceptance of the ESR then the Schottky pickups can monitor mother and daughter nuclides simultaneously 2) the Q -value of the reaction is large enough to allow the resolution of both distributions eventhough the ion charge state remains the same 3) the daughter products are detected by particle detectors at positions where the stored ions are going to leave the closed orbit [50]. In the case of β decay into bound states a large $B\rho$ change can be induced via stripping off electrons in the internal gas target of the ESR [6]. The Schottky pickup probes are well suited for half-life measurements since the power integral of the Schottky band in the frequency spectrum is strictly proportional to the number of stored ions and the sensitivity is so high that a single, highly charged ion can be identified after a few hundred revolutions in the ring [61].

In the experiment with stored ^{58}Ni fragments half-lives have been measured with Schottky spectroscopy [51]. The decay of cooled fragments was monitored by the change of the peak area in the corresponding frequency spectrum. The absolute velocity of the stored ions was deduced from the terminal voltage of the electron cooler to transform the measured half-life from the laboratory frame to the rest frame of the ion. For long-lived cooled nuclei one has to take into account the atomic interactions of the circulating ions with the cooler electrons (10^8 electrons / cm^2) and the atoms of the residual gas (10^{-11} mbar) in the ESR. Mainly the radiative electron capture (REC) processes with the cooler electrons are responsible for the 'atomic losses'. Due to the excellent mass resolution (fig. 6), for cooled fragment beams the nuclear decay of mass-resolved isomers can be measured. In figure 9 the measured results are illustrated for bare ^{53}Fe (ground state, $7/2^-$) fragments and the isomer ^{53m}Fe ($19/2^-$). The corresponding two mass spectra are overlayed to show the populations 200 s and 600 s after the injection into the ESR. The decay curves

are also presented in the figure. The measured half-life for ^{53}Fe is 8.5(3) min and for ^{53m}Fe 2.48(5) min which are in good agreement with the experimental half-lives for neutral atoms since the correction of the modified Fermi function is small in this case. The correction due to atomic charge exchange processes is for this range of half-lives still negligible.

Fig. 9. Half-life measurements of mass-resolved Fe fragments, ^{53}Fe (ground state, $7/2^-$) and the isomeric state ^{53m}Fe ($19/2^-$). Two mass spectra are overlaid which show the populations 200 s and 600 s after the injection into the ESR.

More drastic are the changes in half-lives for heavier bare nuclides and of course for nuclei with a significant nuclear electron capture (EC) branch. In our experimental setup the β decay properties for bare ions can be studied without the admixture of the EC branch. Nuclei which are stable in the neutral state can become radioactive via β decay into bound states. This interesting decay mode was for the first time experimentally identified for bare $^{163}\text{Dy}^{66+}$ nuclei stored in the ESR [6]. Recently the bound state beta decay of $^{187}\text{Re}^{75+}$ ions was discovered. This nucleus is of great importance as an astrophysical chronometer [62]. The reliability of such a clock is however dependent on the fact that the $^{187}\text{Re}^{75+}$ ions are highly ionized in the hot plasma of a star, i.e., corrections due to bound state beta decay have to be applied for this clock. The half-life of neutral $^{187}\text{Re}^0$ atoms is $4 \cdot 10^{10}$ years which is much larger than

the lifetime for the bare nucleus. The present experiment [62] determined a value of 33 ± 2 years for $^{187}\text{Re}^{75+}$ which is in agreement with the theoretical predictions [63].

In summary, the ISOLTRAP and the FRS-ESR facilities represent a new generation of experimental tools. The illustrated examples should give only a first impression of the potential for challenging studies with secondary nuclear beams.

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