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Experiments with Stored Relativistic Exotic Nuclei

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Abstract. Beams of relativistic exotic nuclei were produced, separated and investigated with the combination of the fragment separator FRS and the storage ring ESR. The following experiments are presented: 1) Direct mass measurements of relativistic nickel and bismuth projectile fragments were performed using Schottky spectrometry. Applying electron cooling, the relative velocity spread of the circulating secondary nuclear beams of low intensity was reduced to below 10^{-6} . The achieved mass resolving power of $m/\Delta m = 6.5 \cdot 10^5$ (FWHM) in recent measurements represents an improvement by a factor of two compared to our previous experiments. The previously unknown masses of more than 100 proton-rich isotopes have been measured in the range of $54 \leq Z \leq 84$. The results are compared with mass models and estimated values based on extrapolations of experimental values. 2) Exotic nuclei with half-lives shorter than the time required for electron cooling can be investigated by time-of-flight measurements with the ESR being operated in the isochronous mode. This novel experimental technique has been successfully applied in a first measurement with nickel fragments. A mass resolving power of $m/\Delta m = 1.5 \cdot 10^5$ (FWHM) was achieved in this mode of operation. 3) Nuclear half-lives of stored and cooled bare projectile fragments have been measured to study the influence of the ionic charge state on the beta-decay probability.

INTRODUCTION

The study of exotic nuclei is an important challenge in nuclear physics and has revealed exciting new nuclear properties which are not present close to the valley of beta stability [1,2]. Research of nuclear structure is extended by new secondary beam facilities, where recently special effort has been devoted to experiments using radioactive nuclei at energies above the Coulomb barrier [3].

An advantage of exotic nuclear beams at relativistic energies is that the reaction products are bare or populate only few-electron states. Indeed, the selection of the projectile energy can be used to prepare the fragments in desired charge-state distributions [4]. This situation allows experiments under conditions which prevail in stellar plasmas and are therefore relevant for basic astrophysical studies [5,6].

In addition to the ion-optical performance of a separator system, the atomic interactions (slowing-down characteristics and charge-state population) of the ions determine the isotopic separation quality and particle identification [7,8]. Advantages of relativistic secondary beams have been demonstrated at the fragment separator FRS with the identification of the two doubly magic nuclei ^{78}Ni [9], ^{100}Sn [10], and of 117 new fission fragments. New nuclear structure properties of halo nuclei have been discovered using the FRS as a high-resolution spectrometer [11–13].

In this contribution we will concentrate on mass and half-life measurements of relativistic projectile fragments performed with the unique combination of the FRS

FIGURE 1. Range of FRS-ESR mass measurements covered in experiments with ^{209}Bi projectile fragments in 1995 and 1997. In the latter experiment we extended the measured mass surface down to cesium and also to neutron-rich fragments near the shell closures at $Z=82$ and $N=126$. The marked areas of our studies represent the previously unknown masses only.

and the experimental storage ring ESR [14,15]. The progress of mass measurements are presented in some recent review articles [16–18].

Our mass measurements with stored fragments in the ESR covered a large area of proton-rich nuclei $54 \leq Z \leq 84$ which includes also members of α -chains linked by precise Q_α values but not yet connected to the backbone of known masses [19]. An overview of the mass surface covered by our mass measurements with ^{209}Bi projectiles is shown in fig. 1. The isotopes with masses known before our experiments as well as those where new mass measurements were performed in 1995 and 1997 are indicated in a section of the chart of nuclides. In our 1997 experiment we extended the measured mass surface to smaller Z values down to cesium ($Z=55$) and also to neutron-rich fragments near the shell closures at $Z=82$ and $N=126$.

MASS SPECTROMETRY OF STORED RELATIVISTIC IONS AT THE SIS-FRS-ESR FACILITY

Stable beams of relativistic heavy ions provided by the synchrotron SIS [20] with a maximum magnetic rigidity ($B\rho$) of 18 Tm are converted into exotic nuclei by nuclear collisions in the production target at the entrance of the spectrometer FRS. Projectile fragmentation and projectile fission combined with in-flight separation are versatile tools for experiments with relativistic exotic nuclei [3]. The FRS separates the fragments in flight and injects them into the ESR [14] for precise mass determination, performed by measuring the revolution frequency of the stored ions. The ESR is equipped with an electron cooler [24] and can store ions in the range of $(0.5 \leq B\rho \leq 10)\text{Tm}$. The storage time of the nuclei (τ_{st}) is limited by atomic collisions with atoms of the residual gas (pressure $\leq 10^{-10}$ mbar) and with the electrons of the cooler. τ_{st} can range from hours up to days depending on the velocity and the charge state of the stored ions. The phase-space density of the stored ions can be drastically reduced by electron cooling, e.g., the relative velocity spread of a low-intensity cooled beam can be less than 10^{-6} .

Two methods are employed to perform precise mass measurements of stored ions circulating in the ESR: 1) Mass spectrometry using cooled ion beams. 2) Mass spectrometry of hot fragments operating the ESR in the isochronous mode. Both principles can be easily understood by

$$\frac{\Delta m}{m} = -\gamma_t^2 \frac{\Delta f}{f} + (\gamma_t^2 - \gamma^2) \frac{\Delta v}{v}, \quad (1)$$

the first-order relation between the mass m , the revolution frequency f , and the velocity v . The mass resolution is given by the precision achieved for the frequency and velocity determination. The formation of the exotic nuclei always causes a relatively large velocity spread, which is inherent due to the nuclear reaction dynamics and depends on the selected fragments. γ is the relativistic Lorentz-factor and γ_t represents the reduced transition energy which characterizes the ion-optical

mode of the ring. From this formula it is obvious that either cooling $\frac{\Delta v}{v} \rightarrow 0$ or the isochronous condition, $\gamma \rightarrow \gamma_t$, are the basis of precise mass measurements.

Schottky Mass Measurements with Cooled Fragments

Schottky spectroscopy is widely used for beam diagnosis in circular accelerators and storage rings. The induced signals of the stored circulating ions in non-destructive probes are recorded and analyzed. Already in our pilot experiments with cooled projectile fragments [15,21] we have applied Schottky diagnostics and since then we are gradually developing this technique for the requirements of precision mass spectrometry [19,22,23]. The stored and cooled ions circulate in the ESR with revolution frequencies of about 1.9 MHz. In the experiment we used the Schottky-noise signal of the 32th harmonic of the revolution frequencies. This high-frequency band has to be reduced by mixing with an external oscillator to match the working range of 1 kHz to 300 kHz of the Fourier-analyzer system. An improved data-acquisition system digitizes the Schottky signals with a sampling rate of 625 kHz. The data are sequentially recorded on tape with the time correlation of the events. The frequency bandwidth of 200 kHz covers most of the $B\rho$ acceptance of the stored beam in the ESR. Fast Fourier transformation of the time-correlated data can be performed off-line in order to obtain the revolution frequencies of the stored ions as well as the half-life information of the radioactive species. Furthermore, undesirable drifts of the experimental conditions can be corrected in the off-line analysis. In the 1997 experiment we used ^{58}Ni and ^{209}Bi projectiles and set the magnetic fields of the FRS and ESR and the cooler voltage corresponding to a constant $B\rho$ value of 6.5 Tm. This means for example, that the kinetic energy of ions with a mass-over-charge ratio of 2.35 is 315.6 A·MeV. This energy range allowed an optimum performance of the electron cooler and, in addition, presented the opportunity to measure the masses of bismuth fragments in bare, H-like, and He-like charge states. The mass measurement in different charge states yields not only redundant data for the same isotope, but is also advantageous for the calibra-

FIGURE 2. Calculated ionic charge state population of heavy ions [4] emerging from a beryllium target with velocities corresponding to a fixed magnetic rigidity of 6.5 Tm. Masses of stable nuclei are used in these calculations.

tion. Reference masses in different ionic charge states are automatically included in the corresponding $B\rho$ settings and appear in this way in the neighborhood of the isotopes with unknown masses in frequency spectra. The rest mass of the electron and its binding energies are known with an accuracy of the order of 10^{-10} . This uncertainty is completely negligible compared to our present errors for the nuclear masses [19] being in the order of 10^{-6} . The incident energy of the projectiles, focused on the production targets at the entrance of the FRS, was varied to select different fragments for injection into the ESR. The production targets were 4 and 8 g/cm² beryllium for the ⁵⁸Ni and ²⁰⁹Bi projectiles, respectively. The ionic charge state population of fragments emerging from the targets with velocities corresponding to the fixed magnetic rigidity of 6.5 Tm is shown in fig. 2. The populations were calculated by computer codes which are based by heavy ion charge state measurements at GSI and LBL [4]. The fragments were separated with the FRS by pure $B\rho$ analysis during the major part of the mass measurements. In this case up to 60 different fragments were injected into the ESR by a single bunch of projectiles from SIS. However, we also successfully applied the $B\rho$ - ΔE - $B\rho$ separation method [7] and stored and cooled a monoisotopic beam in the ESR, as discussed below. A number of important improvements could be achieved between the 1995 and the 1997 mass measurements: A new data acquisition system was taken into operation (see above). The performance of the ESR cooler was considerably improved yielding a much stronger cooling force which led to shorter cooling times and, therefore, gave access to isotopes with shorter half-lives. Furthermore, the better stabilization of the power supplies and the improved field homogeneity of the ESR magnets helped to significantly improve the resolving power in the mass spectra. In fig. 3 we present Schottky frequency spectra for bismuth and nickel fragments characterized by a mass resolving power of $6.5 \cdot 10^5$ which is about a factor of two better than in our 1995 experiment [19]. It should be mentioned that the half-life of neutral ^{151m}Er atoms is 0.58 s, however, in our case with bare nuclei the half-life is prolonged by roughly a factor of 21, see below.

FIGURE 3. Mass resolved Schottky frequency spectra of bare ^{151g,m}Er ions (ground and isomeric states separated by 2585 keV, left panel) and of bare ^{44g,m}Sc ions (ground and isomeric states separated by 271 keV, right panel)

Isochronous Mass Measurements with Hot Fragments

Exotic nuclei with half-lives shorter than the cooling time can be investigated by the time-of-flight techniques where the ESR is operated in the isochronous mode [25,26]. In this case, the magnetic fields of the ESR quadrupole and hexapole magnets are set such that the revolution frequency of an ion species becomes independent of its velocity, see equation (1). This novel experimental technique has been successfully applied in first measurements with nickel fragments [26]. The ESR lattice was tuned to $\gamma_t=1.37$ corresponding to a kinetic energy of 345 A·MeV for the stored ions. γ_t is mainly determined by the dispersion function inside the dipole magnets. The first frequency spectra recorded in the isochronous mode are shown

FIGURE 4. First frequency spectra of hot fragments recorded in the isochronous mode of the ESR. Left panel: Nickel fragments and the primary beam (^{58}Ni) simultaneously injected within the same window of the $B\rho$ acceptance of the ESR. Right panel: Frequency spectrum of ^{52}Fe and of the doubly magic nucleus ^{56}Ni measured in the isochronous mode.

in fig. 4. In the left panel the primary beam (^{58}Ni) and the fragments in the same window of the $B\rho$ acceptance of the ESR injection are shown. The relative velocity spread of these stored ions was about 10^{-3} . Although the momentum acceptance inside the ESR is strongly reduced in the isochronous mode, as compared to the standard operation, the measured m/q acceptance still reached 1.2%. Already in this pilot experiment we achieved a remarkable mass resolving power of $m/\Delta m = 1.5 \cdot 10^5$ (FWHM) as demonstrated by resolving ^{56}Ni and ^{52}Fe fragments, see the right panel of fig. 4. In the off-line analysis the measured dependence of the frequency on the velocity could be well understood and was reproduced by ion-optical model calculations. New ion-optical calculations suggest strong improvements for the isochronous mode which will be tested in future experiments [27].

RESULTS OF THE MASS MEASUREMENTS

After having demonstrated that the results obtained with our novel experimental methods for direct mass measurements agree well with already known light masses, a large number of isotopes with unknown masses has been measured (fig. 1). The interesting nuclides have been produced via fragmentation of bismuth projectiles.

FIGURE 5. Differences of masses from the 1995 experiment obtained by Schottky spectrometry and from the Audi-Wapstra table [28] for $Z=80, 82, 84$. The bold bars represent the errors of the experimental data, whereas the thin bars indicate the uncertainties given in the mass table.

As already mentioned, the population of different charge states served as an excellent tool for unambiguous identification and redundant determination of ionic masses from frequency spectra. In particular, the H- and He-like proton-rich nuclei appeared in the spectra in the neighborhood of bare nuclei which are positioned closer to the valley of beta stability and have very well known masses used for calibration of the frequency scale. The masses were evaluated by application of the maximum likelihood method. The relation of the mass-over-charge ratio as a function of the revolution frequency was fitted by a first-order polynomial connecting the known masses as references [28]. The unknown masses were determined by searching the maximum of the probability density for all data. The total error of the new masses is in the range of 100 to 200 keV, where a systematic error of about 95 keV has been included. The systematic error has been evaluated by a comparison with previously well-known masses. In the following, some of the data measured in the 1995 experiment are compared with the tabulated values derived from systematics [28]. The comparison presented in fig. 5 demonstrates that, in general, our data are in good agreement with the values of the mass table [28]. The good accuracy of our measured data is a solid basis for a better understanding of the nuclear forces. The comparison of the data with microscopic theories yields new insight for the different models based on the nucleon-nucleon interactions parametrized as nuclear forces (e.g. Skyrme, Gogny) [29,30]. However, at the present status of

FIGURE 6. Measured 1-proton separation energies (Exp) for mercury, lead, and polonium isotopic chains compared with model predictions. The abbreviations for the different theoretical models are explained in the text. The experimental errors are smaller than the symbols.

FIGURE 7. Differences of the measured masses for mercury, lead, and polonium isotopic chains and the corresponding model predictions [32–34]. The experimental errors are those displayed in fig. 5.

the microscopic theories the deviations from the experimental results are still up to several MeV. Progress in this field might be expected from modern Hartree-Fock-Bogoliubov calculations and Relativistic Mean Field theory which yield also reliable microscopic descriptions of other nuclear properties, like radii, of course using the same nucleon-nucleon interactions as employed for the mass predictions. This subject is for example reviewed in the theoretical contribution by P. Ring [31] at this conference. Therefore, we restrict ourselves here to comparisons with the Macroscopic-Microscopic (MM) [32] approach, with predictions based on the Thomas-Fermi model (TF) [33], and with the Extended Thomas-Fermi model with Strutinski Integral (ETFSI) [34]. In fig. 6 our experimental 1-proton separation energies, are compared to the MM, TF, and ETFSI predictions. In general, a stronger staggering effect between even and odd masses is observed in the experimental data, in particular for the most proton-rich isotopes, as compared to the mass model predictions. This observation clearly indicates that the description of the pairing force has to be improved. The need for improvements of the theoretical models is even more obvious from the comparison of absolute mass differences, as depicted in fig. 7. In the future direct mass measurements will be extended to shorter-lived nuclei using the isochronous method. However, there are also regions on the chart of nuclei where the Schottky mass spectrometry can still significantly contribute to an improved knowledge of the mass surface. The better mass resolution as well as the successful development of the stochastic cooling in the ESR [35], decreasing the cooling time for hot fragments, will considerably enhance the potential of Schottky mass spectrometry of cooled exotic nuclei.

LIFETIME MEASUREMENTS OF STORED RELATIVISTIC IONS

Mass and half-life measurements both address fundamental properties of atomic nuclei. In the case of half-life measurements at relativistic energies, one has a unique possibility to study the nuclear decay as a function of the ionic charge state [36]. Decay studies of bare and few-electron radioactive ions are of fundamental interest and are also relevant for the understanding of nuclear decay and reactions in stellar

plasmas. The possibility to access bare nuclei in the laboratory is experimentally also quite advantageous as demonstrated with our example with ^{151m}Er nuclei where the half-life prolongation allowed to apply Schottky mass spectrometry.

Half-lives can be measured in the ESR via the decreasing intensity of stored mother nuclei [21], by directly detecting the daughter nuclides, or even by both. The decay of stored nuclei can be measured in several scenarios: 1) If the magnetic rigidity difference between mother and daughter nuclei is within the 3.6 % acceptance of the ESR, then the Schottky pickups can simultaneously monitor both species. This represents a unique possibility. 2) The ionic charge state remains the same, however, the Q-value of the decay is large enough to allow the separation of both frequency signals. 3) The daughter products are detected by particle detectors at positions where they are going to leave the closed orbit of the mother nuclei [15]. In the case of β decay into bound states, a large $B\rho$ change can be introduced via stripping off the decay electron in the internal gas target of the ESR [5,6]. Half-life measurements of stored ions using the time-dependent intensities of both the mother and daughter nuclei require that the daughter is not already dominantly present in the circulating beam or that it cannot be formed by the decay of other stored nuclei. Therefore, it is desirable to have a monoisotopic beam stored in the ESR.

The feasibility of this method at the FRS-ESR is demonstrated by applying the $B\rho\text{-}\Delta E\text{-}B\rho$ method [7] for nickel fragments with the goal to measure the half-life of the ^{52m}Mn isomer. In fig. 8 Schottky spectra are shown for stored fragments without (left panel) and with a degrader (right panel) placed in the midplane of the FRS. In the latter case, the FRS-ESR system was set to transmit and accept only bare $^{52g,m}\text{Mn}^{25+}$ ions which are separated only by 378 keV. The experimental results successfully illustrate the injection and storage of monoisotopic beams. The

FIGURE 8. Measured cooled nickel fragments in the ESR after separation with the FRS by pure $B\rho$ analysis (left panel) and by applying the $B\rho\text{-}\Delta E\text{-}B\rho$ method [7] with an intermediate degrader (right panel). In this broad-band spectrum the ground and isomeric states of ^{52}Mn nuclei are not resolved.

FIGURE 9. Half-life measurements of the mass resolved ^{52}Mn isomer (decay curve, left panel). The ground and isomeric states are well separated in the Schottky mass spectra (right panel). The excitation energy is 378 keV and the measured mass resolving power is $5.5 \cdot 10^6$.

improved mass resolving power in our recent experiments is clearly demonstrated in fig. 9 where the ground and isomeric states of ^{52}Mn nuclei are well resolved in the Schottky frequency spectrum. The decay of cooled fragments was monitored by the change of the peak area in the corresponding frequency spectrum. The basic assumption is that in this measurement the area of a Schottky frequency peak is strictly proportional to the number of stored ions. 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. In the left panel of fig. 9 the decay curve for the bare isomer ^{52m}Mn ($J^\pi=2^+$) is shown. The measured half-life of ^{52m}Mn is 22.7 ± 3.0 min where the particle losses due to atomic interaction were taken into account from the storage time of the much longer-lived ground state $T_{1/2}(^{52g}\text{Mn}) = 5.59$ d. The result is in good agreement with the experimental half-life for neutral atoms because no major decay branch was suppressed in the bare state, and because the correction of the modified Fermi function is small in this case [21].

A goal for our half-life studies in the future is to systematically investigate the beta decay of heavier ions as a function of the ionic charge. The influence of screening and the branch of beta decay into bound states are further items which can be ideally investigated with the new data acquisition developed for the Schottky mass spectrometry.

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