New results on atomic masses and nuclear decay rates from experiments at FRS-ESR

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Abstract

New experimental results on gross properties of exotic nuclear beams, studied at FRS-ESR, are presented: the direct observation of bound-state beta-decay, half-lives of bare nuclei in isomeric states, and nuclear binding energies of neutron-rich fission fragments.

1 Introduction

Nuclear binding energies and half-lives of exotic nuclei provide key information for open questions in nuclear astrophysics, for weak interaction studies, and for basic nuclear and nuclear-structure physics. For the present experiments the FRS acts as an ion source and in-flight separator for exotic nuclei, and the ESR is used as a high-resolution mass spectrometer. The production and separation of exotic nuclei at relativistic velocities using the in-flight technique [1] at the FRS yields few-electron or even bare nuclei, because their velocity is similar to or even exceeding the orbital electron velocities. When such ions are stored in the storage ring ESR, their decay properties can be studied under conditions which prevail in a stellar plasma with temperatures of the order of 100 keV. It is obvious that all those decay modes are affected, where electrons of the atomic nucleus are involved in the decay, and half-life modifications are to be expected. Such processes can be uniquely studied at the ESR and in the following exciting new results from the nuclear-physics experimental programme at FRS-ESR will be presented.

2 Half-life studies of bare nuclei

A new decay mode is the bound-state beta decay, the time-mirrored orbital electron capture, where the electron, which is released in the nuclear decay, becomes bound in an inner atomic shell of the daughter nucleus [2], see left part of Fig. 1. Bound-state beta decay is a negligible effect in neutral atoms, but may become a significant decay channel when ions become highly or fully ionized. It was shown by Takahashi [3], that for bare isotopes the branching ratio for bound and continuum beta decay depends only on the Q-value, see center part of Fig. 1. For small Q-values bound-state beta decay may become the only energetically possible decay process, because the electron cannot be emitted to the continuum when the Q-value is smaller than the electron binding energy. The bound-beta decay rate decreases with increasing Q-value because of the decreasing phase-space overlap between the initial and final state. In a recent experiment, the bound-state beta decay of bare $^{206}\mathrm{Tl}^{81+}$ and $^{207}\mathrm{Tl}^{81+}$ was directly observed [4], see right part of Fig. 1. From a full analysis of these experimental data a wealth of unique information can be obtained [4]: total and partial β_b-lifetimes, the Q-value for β_b, and the 'Fermi-function', which is the ratio of bound and continuum electron wave function at the origin. This function has been probed for β^+- and electron-capture decay, but never before for β^--decay.

The opposite behaviour, the blocking open decay channels due to the absence of atomic shell electrons, can be studied in isomeric states with low transition energies, where internal conversion dominates, as for instance in the decay of the isomeric state of bare $^{151m}\mathrm{Er}$ [5]. There, the observed decay rates are drastically smaller than the literature values given for neutral atoms, because electron conversion is impossible. When being a neutral atom, the isomeric state in $^{151}\mathrm{Er}$ is characterized by a half-life of 0.58 s and an excitation energy of 2.568 MeV, and it decays with 95 % probability by internal conversion via an E3 transition with 58 keV and with 5 % by β^+ and electron capture. In the bare nucleus only β^+-decay and γ-emission remain as open decay channels and from a detailed calculation [5] a half-life $T_{1/2}(^{151m}\mathrm{Er}^{68+}) = 16 \pm 1$ s is obtained.

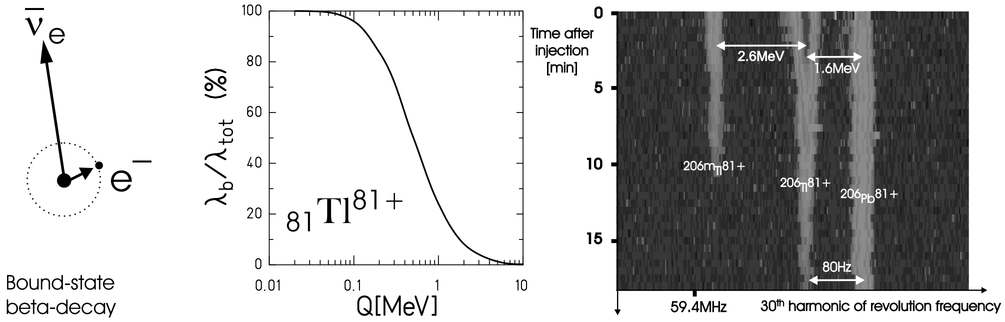

Figure 1: Left: sketch of the bound-state beta decay, where the electrons are captured into bound atomic states and monochromatic antineutrinos are emitted. Center: Ratio of decay rate for bound-state beta decay (λ_b) and total decay rate (λ_tot) as a function of Q-value [3] for fully ionized Tl ions. Right: first direct observation of bound-state beta decay, showing the traces of bare mother ($^{206m,g}\mathrm{Tl}^{81+}$) and hydrogen-like bound-beta-decay daughter ($^{206}\mathrm{Pb}^{81+}$) nuclei, observed for approximately 20 minutes [4].

This value is in excellent agreement with the result of the first experimental observation of this effect, where a half-life $T_{1/2,\,\mathrm{exp.}} = 19\pm3$ s [5] was measured.

3 Nuclear binding energies of exotic nuclei

Atomic mass measurements are key experiments for the exploration of unknown territory in the chart of nuclei, and the systematic investigation of the total binding energy of exotic nuclei reveals distinct basic information on the isospin dependence of nuclear forces, on nuclear-structure effects far off stability such as shell structure and deformation, and on the limits of stability.

Two complementary, new techniques, Schottky-Mass-Spectrometry (SMS) [6, 7] and Isochronous-Mass-Spectrometry (IMS) [8], have been developed during the last years and were used in several experimental runs for mapping large areas of the nuclidic mass surface. Employing SMS in two runs, where neutron-deficient nuclei were produced by bismuth fragmentation [7, 9], masses of almost 350 different isotopes were directly determined, more than 150 of them were previously unknown according to ref. [10]. Some additional 90 new masses could be obtained by using the links of α-chains, leading to one of the most important results of these experiments: the location of the proton-drip-line in the region of francium [7, 11]. Moreover, the shell gap energy of neutron-deficient lead isotopes is probed and yields new insights on the deformation effects in this area [11, 12].

Neutron-rich nuclei are of special interest. It is assumed that the elements heavier than iron are produced in explosive processes in stars such as supernova explosions by an interplay of rapid neutron capture and subsequent beta-decay, a process which is therefore called r-process. The capture of neutrons leads far away from stability to neutron-rich isotopes, which have small neutron-separation energies, comparable to the temperature of the star.

Neutron-rich nuclei can be produced at the FRS by fission of high-energy uranium projectiles and already the first experiments led to the discovery of many new isotopes [13]. After injection into the ESR, their masses can be determined from the precise measurement of their revolution time. Since most of the fission fragments have half-lives of the order of several milliseconds, Isochronous Mass Spectrometry (IMS) [8] is used, a method which has the potential to investigate nuclides with half-lives down to the microsecond range (see below). The ESR, operated in an isochronous ion-optical mode, is used as high-resolution mass spectrometer, and a mass resolving power of $m/\Delta m \simeq 100000$ (FWHM) and a mass precision of typically 100 keV is achieved.

A peculiarity of the fission kinematics of relativistic projectiles can be used in order to inject efficiently the most neutron-rich isotopes and suppressing at the same time the much more abundantly produced isotopes closer to the stability line. This can be understood from Fig. 2. The figure shows the kinetic energy of ^{135}Sn^{50+} fission fragments as a function of the spatial angle when leaving the production target at the entrance of the FRS. In the center-of-mass system the fission fragments are spatially isotropically distributed and both fragments share the available energy (which is the energy equivalent of the mass difference between the projectile and the sum of both fragments). After transformation into the laboratory frame, the fission fragments cover a wide range of kinetic energies, depending on the angle of emission relative to

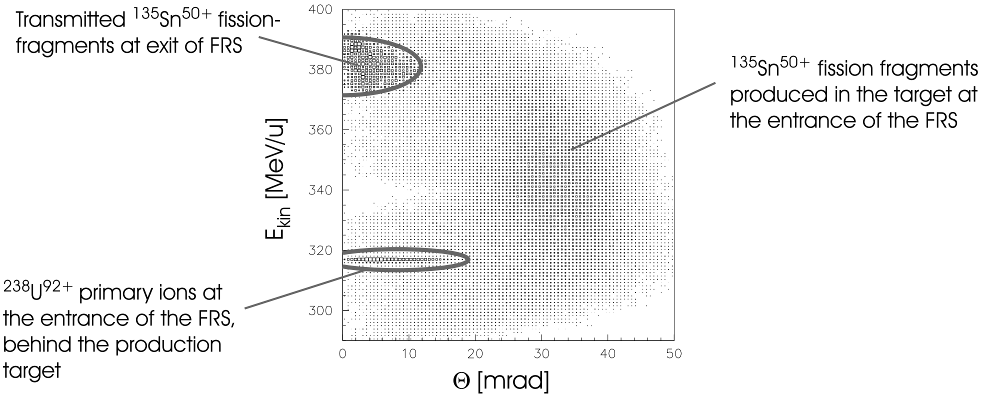

Figure 2: Result of a MOCADI simulation [14]: energy distribution of ^{135}Sn^{50+} fission fragments as a function of the spatial angle relative to the direction of the incident primary beam.

the direction of the primary beam. The available energy of $\approx$ 200 MeV is converted into a variation of up to more than 100 MeV/u between the forward and backward emitted fragments. The fragments emitted in forward direction leave the target with a velocity, which is up to 6 % larger than that of the primary beam. For these 'fast' fragments, most of the fission energy has been converted into kinetic energy. Optimizing the FRS-ESR settings on these 'fast' fragments, the neutron-rich isotopes are preferably transmitted and the less neutron-rich fragments, which are 'slower', are suppressed.

The mass of many nuclides, whose mass is so far only known from theoretical predictions, is now determined for the first time in this experiment. An overview of the investigated area, showing the nuclides with known and unknown masses with respect to the compilation of atomic masses from 1995/1997 [10] as well as the new masses determined in this experiment, are depicted in Fig. 3.

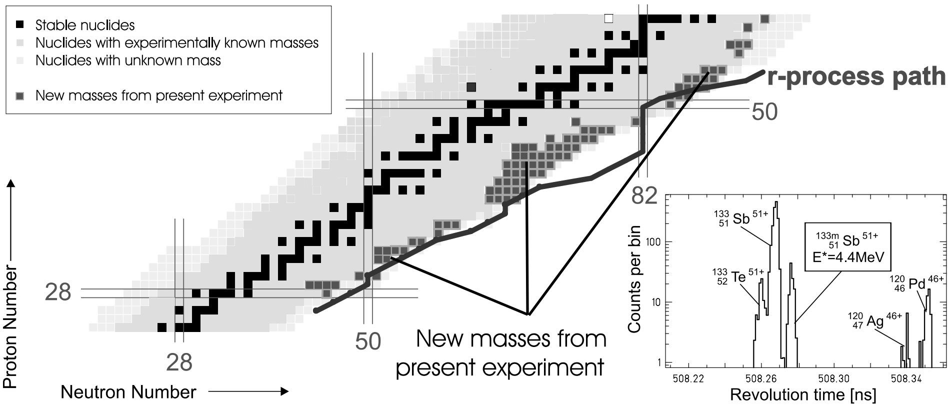

Figure 3: Part of a schematic chart of nuclei. Atomic masses, which have been determined for the first time in experiments at FRS-ESR are indicated. The inset shows a zoomed part of a revolution-time spectrum as obtained during the experiment.

These new mass data are of particular interest in nuclear astrophysics, where Q-values, neutron-separation energies, and half-lives are needed for nuclear-reaction network calculations, which aim at modeling the true r-process path in nucleosynthesis and the understanding of the observed elemental and isotopic abundances in the solar system [15]. The data in the vicinity of closed shells ($N = 50, 82,\ Z = 28, 50$) and in particular in the vicinity of double shell closures will allow the investigation of the isospin dependence of shell effects and possible new phenomena like shell quenching.

A striking result of this recent experiment is the capability to study μs-isomers, see inset of Fig. 3. In ^{133}Sb there are two isomeric states known, which have excitation energies $E_1^* = 4.364$ MeV and $E_2^* = 4.526$ MeV and half-lives $T_{1/2,1} = 3$ μs and $T_{1/2,2} = 16$ μs, respectively [16]. The spectrum clearly shows a separated peak next to the ground state of bare ^{133}Sb and a preliminary analysis of the energy difference to the ground state yields 4.4 ± 0.2 MeV. Although the two excited states cannot be resolved, this result highlights the potential of this new experimental technique and the possibility to search for new μs-isomers and to determine their excitation energies.

4 Summary

The FRS-ESR complex opens up a new experimental access to study basic nuclear properties of highly-charged and bare unstable nuclei. Recent highlights from the study of bound-state beta decay, the hindrance of isomeric transitions, the first direct mass measurements of neutron-rich fission fragments along the r-process path and the first observation of μs-isomers in the ESR have been shown.

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