

Mass and Half-Life Measurements of Stored Exotic Nuclei

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1 Time-resolved Schottky Mass Spectrometry

Time-resolved Schottky Mass Spectrometry (SMS) [1, 2, 3] has been applied for direct mass and half-life measurements on neutron-deficient ²⁰⁹Bi fragments, which were separated with the FRS and stored and cooled in the ESR. In this experiment the Schottky noise of the stored ions is recorded continuously. This allows in an off-line FFT analysis to generate frequency spectra which are subsequent in time. In order to achieve a compromise between sufficiently high signal-to-noise ratio and time resolution, each spectrum comprises 30 seconds of measurement time. The mass resolution amounts to $1.5 \cdot 10^{-6}$ (FWHM). The spectra cover the whole acceptance of the ESR, and ultimate sensitivity is reached, i. e., even single ions can be observed. Time-resolved Schottky beam noise analysis can not only be used for mass spectrometry, but it is ideally suited to study dynamic processes in the ESR such as radioactive decays [4]. In particular the decay of mother and the creation of daughter nuclei can be studied, as is illustrated in Fig. 1.

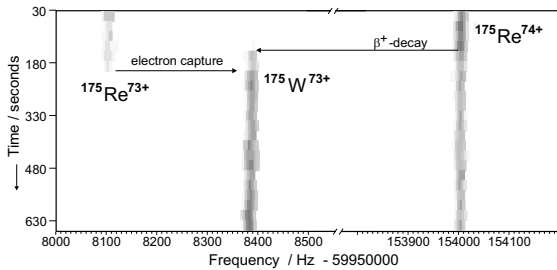


Figure 1: Consecutive 30 s Schottky-noise frequency spectra from top to bottom. The Schottky-noise power density is indicated by the grey-scale. The β^+ decay of a ¹⁷⁵Re⁷⁴⁺ ion is visible, and, 60 seconds later, the electron capture of a single ¹⁷⁵Re⁷³⁺ ion to the same daughter nuclide ¹⁷⁵W⁷³⁺.

The noise power of a frequency peak is proportional to the number of ions. This fact allows us to use time-resolved SMS for half-life measurements. Pioneering experiments on the modification of half-lives for bare ions as compared to neutral atoms have been carried out at the ESR [5]. Here we report on so far unobserved half-life modifications of bare isomers: when an isomeric transition is highly converted, the corresponding decay rate will change drastically when the isomer is fully stripped. An example is the isomeric state in the bare ¹⁵¹Er⁶⁸⁺, whose measured decay curve is shown in Fig. 2. In the neutral atom this isomeric state ($T_{1/2} = 0.58$ s) decays mainly via internal conversion, because the total conversion coefficient $\alpha_{\text{tot}} \simeq 1250$. In the

absence of the atomic electron cloud internal conversion is impossible. The theoretically expected half-life for bare ^{151m}Er⁶⁸⁺ amounts to (16 ± 10) s [6], which is in agreement with the experimentally determined value of (29 ± 14) s in the rest frame of the ion. This value is obtained from the observed decay curve in the laboratory frame (Fig. 2) taking into account charge-changing processes in the residual gas and in the electron cooler and the transformation from the laboratory frame to the rest frame of the ion.



Figure 2: Decay curve of the isomeric state of bare ¹⁵¹Er. The straight solid line is an exponential fit to the data.

The evaluation of half-lives can yield useful information for the proper identification of nuclides, for instance in those few cases, where the assignment from the frequency alone is ambiguous. Another example is shown in Fig. 3, where a single ¹⁹²Tl⁸¹⁺ ion is produced by electron capture of ¹⁹²Pb⁸¹⁺. The ¹⁹²Tl has a long-lived isomeric state with an excitation energy $E^* = (160 \pm 50)$ keV, which cannot be resolved. However, the decay scheme [7] shows that ¹⁹²Pb⁸¹⁺ decays with a probability of 99.9943 % to the ground state. Therefore one can safely assign the observed line in Fig. 3 to the ground state of ¹⁹²Tl.

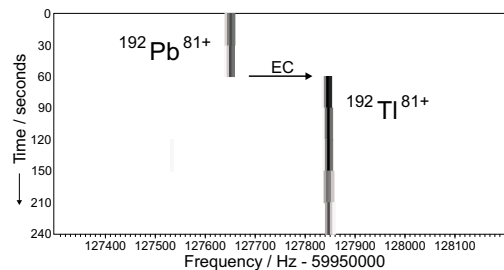


Figure 3: Electron-capture decay of a single stored ¹⁹²Pb⁸¹⁺ ion to ¹⁹²Tl⁸¹⁺.

Meanwhile all raw data have been analyzed and in the experimental spectra about 194000 lines have been identified finding more than 500 different ion species, more than 200 of them having unknown masses [8].

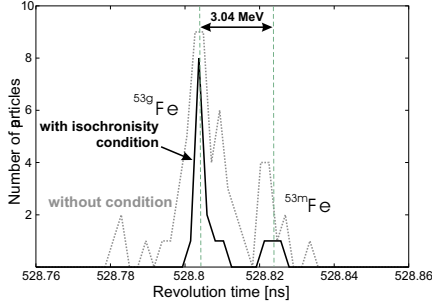


Figure 4: The revolution time spectra of ^{53}Fe illustrate the effect of the isochronicity condition in the data analysis: without this filter a broad and poorly shaped distribution is obtained (dotted line), whereas the application of the filter leads to a clear structure and a distinct separation of the ground and isomeric states (solid line).

2 Isochronous Mass Spectrometry

The masses of neutron-deficient nuclides produced by projectile fragmentation of a 445 MeV/u ^{84}Kr beam in a beryllium target have been measured [9, 10, 11] using isochronous mass spectrometry (IMS) [12, 9]. In this mode cooling is not required, and the ions can be observed for typically 200 μs corresponding to approximately 400 revolutions. The best performance is reached when those particles are rejected from the analysis, whose motion in the ESR is not isochronous thus exhibiting a strong variation of the revolution time, as is illustrated in Fig. 4. The remaining particles fulfill the isochronicity condition [9] very well and for instance the ground and isomeric state of ^{53}Fe are clearly separated. The application of this condition leads to a mass resolving power $m/\Delta m = 110000$ (FWHM). The masses of four short-lived nuclides (^{41}Ti , ^{44}V , ^{45}Cr , ^{48}Mn) with half-lives down to values as low as 50 ms have been measured for the first time [10, 11]. In Fig. 5 the new mass values are compared with the values predicted by several mass models, which deviate from the experimental results by up to 2.8 MeV. These new data contribute to put rp-process model calculations for stellar nucleosynthesis on a solid basis, but more measurements in this area are imperative.

Finally, an interesting observation has been made when comparing the present results to literature values for nuclides with known mass [8]. All data are in agreement except for ^{43}Ti , where a clear deviation of almost 300 keV is observed (upper panel of Fig. 6). Looking at the revolu-

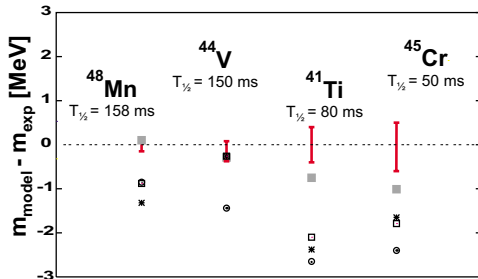


Figure 5: Comparison of new mass values with the predictions of different mass models: ETFSI with SkSc18 (crosses) [13]; HF BCS with MSk7 (open rectangles) [14]; Mac-Mic TF Model (filled rectangles) [15]; Mac-Mic FRLDM (circles) [16].

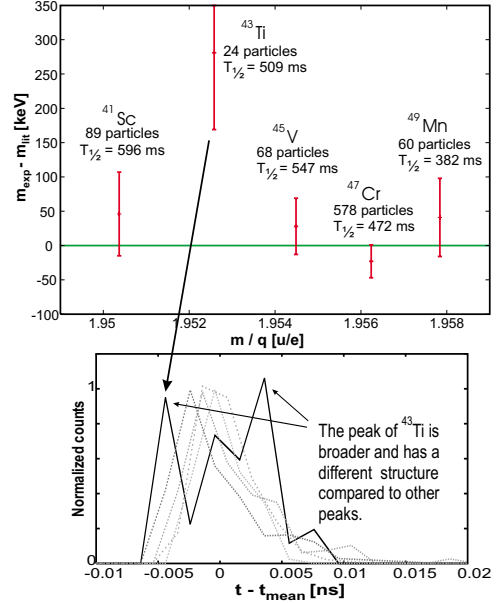


Figure 6: The comparison of the results from IMS to the literature [8] shows good agreement (top panel) except for ^{43}Ti . The bottom panel illustrates that the revolution time peak of this nuclide is broader than similar neighboring lines (in this representation all lines are overlaid by shifting them to the same mean revolution time t_{mean}). Both observations indicate a contamination with an isomeric state.

tion time spectrum and comparing the line shape of ^{43}Ti to that of the other nuclides, significant differences become visible (lower panel of Fig. 6). Since the identification is unambiguous, we interpret this observation as an indication that some of the analyzed 24 particles are in an isomeric state of ^{43}Ti , which is characterized by an excitation energy $E^* = 313$ keV and a half-life of 12.6 μs [17]. This shows that IMS is applicable even to such rapidly decaying nuclides.

References

- [1] M. Falch, Thesis, LMU München (2000).
- [2] T. Radon *et al.*, Nucl. Phys. **A 677** (2000) 75.
- [3] Yu.A. Litvinov *et al.*, GSI Rep. 2001-1 (2001) 16.
- [4] Yu.A. Litvinov *et al.*, Hyp. Int. **132** (2001) 283.
- [5] M. Jung *et al.*, Phys. Rev. Lett. **69** (1992) 2164, H. Irnich *et al.*, Phys. Rev. Lett. **75** (1995) 4182.
- [6] Yu.A. Litvinov *et al.*, publication in preparation.
- [7] R. Firestone, V. Shirley, *Table of Isotopes*, 8th ed., J. Wiley & Sons (1999).
- [8] G. Audi *et al.*, Nucl. Phys. **A624** (1997), 1.
- [9] M. Hausmann *et al.*, Hyp. Int. **132** (2001) 289.
- [10] J. Stadlmann, Thesis, JLU Giessen (2002).
- [11] J. Stadlmann *et al.*, publication in preparation.
- [12] M. Hausmann *et al.*, NIM **A446** (2000) 569.
- [13] Y. Aboussir *et al.*, ADNDT **61** (1995) 127.
- [14] S. Goriely *et al.*, ADNDT **77** (2001) 311.
- [15] W.D. Myers *et al.*, Nucl. Phys. **A601** (1996) 141.
- [16] P. Moeller *et al.*, ADNDT **59** (1995) 185.
- [17] J.A. Cameron *et al.*, NDS **92** (2001) 882.