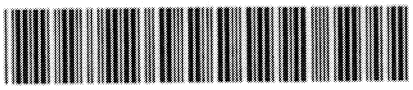

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Precision Experiments with Time-Resolved Schottky Mass Spectrometry *

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A large area on the mass surface of neutron-deficient nuclides ($36 \leq Z \leq 85$) was measured with time-resolved Schottky mass spectrometry at the FRS-ESR facilities The masses of 114 nuclides were obtained for the first time from which 43 were determined via known decay energies The improved mass accuracy of 30 keV allowed to study the isospin dependence of nuclear pairing, to precisely locate the one-proton dripline for odd-Z isotopes from Tb to Pa and to make crucial tests of the predictive powers of modern mass models

1 Introduction

Accurate experiments on nuclear masses yield new insights into the basic nuclear properties such as the limits of their existence, the shell structure, the shapes and pairing correlations

Schottky Mass Spectrometry (SMS) is ideally suited for precise direct mass measurements of a large number of nuclides in one experiment [1,2] Here we present characteristic new results obtained with the novel method of time-resolved SMS

2 Experiment and Analysis

Exotic nuclei were produced by projectile fragmentation of a (600-900) MeV/u ^{209}Bi primary beam in (4-8) g/cm^2 beryllium targets placed at the entrance of the fragment

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separator (FRS) [3] The fragments were spatially separated in-flight and injected into the cooler-storage ring ESR [4] The magnetic rigidity of the FRS-ESR was fixed to 6 5 Tm for the whole experiment, i e the change of the selected fragments was done by varying the incident energy of the primary beam

In the ESR, the velocity spread of the stored fragments was reduced by electron cooling to about $\delta v/v \approx 5\ \ 10^{-7}$ This condition provides an unambiguous relation between the revolution frequencies of the ions and their mass-to-charge ratios which is the basis for SMS The time required for the electron cooling was about 10 s [5]

The stored ions induce image charges on pick-up probes which are amplified, continuously sampled and stored for off-line Fourier analysis The analyzed data yield noise-power density spectra which reflect the revolution frequencies of stored ions

The SMS has reached the ultimate sensitivity recording single ions stored in the ESR [6, 7] This achievement is illustrated in Fig 1 with nuclear electron capture decay of single ^{155}Ho ions and is one of the reasons for the significantly improved resolving power Since a single stored ion is either in the ground or isomeric state it is possible to assign the measured frequencies to one of them Fig 2 shows the distribution of mass values evaluated with the frequencies corresponding to ^{197}Hg single ions In this way a mass resolving power of more than 2 10^6 was achieved Isomeric states with excitation energies above 300 keV are clearly resolved with this method [8]

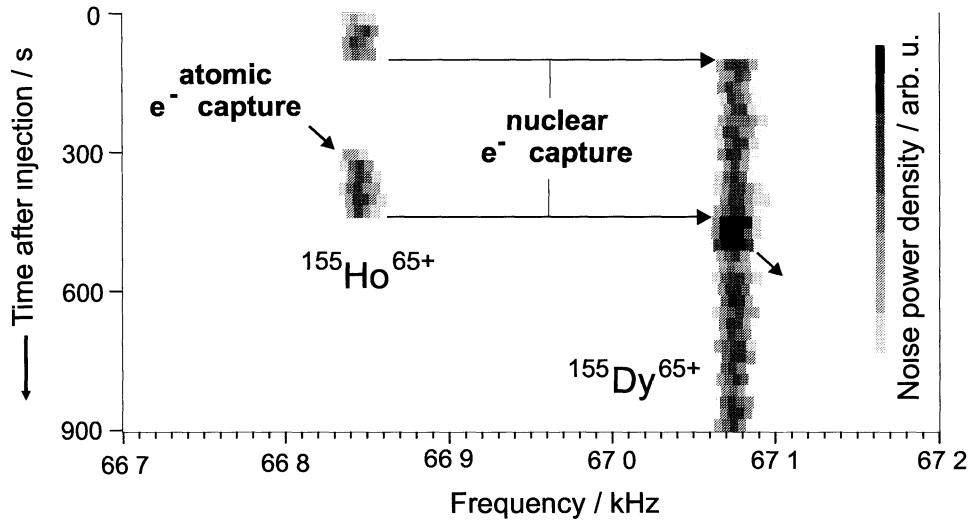

Figure 1 Schottky frequency spectra, subsequent in 30 s time intervals, demonstrating the nuclear electron-capture decay of single ^{155}Ho^{65+} ions The second ^{155}Ho^{65+} ion was created by atomic electron-capture in the cooler

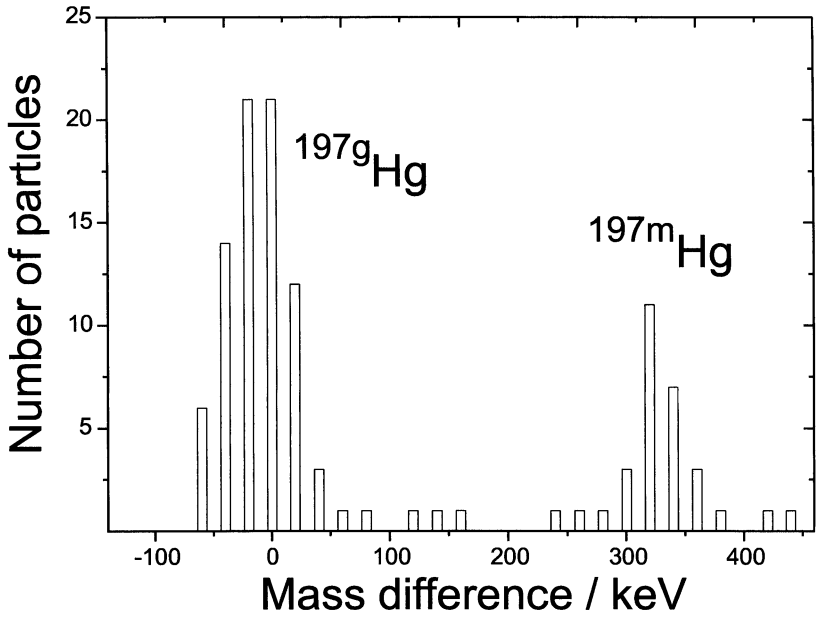

Figure 2 Histograms of mass values evaluated from measured frequencies of single stored ions only The power of this novel method is demonstrated with ^{197}Hg ions where the ground and isomeric states (E^*=299 keV [9]) are clearly separated The mass resolving power in this case is above 2 10^6

3 Results

In this new experiment with time-resolved SMS, 583 different nuclides were observed in the frequency spectra From this set of nuclei, 117 were used for calibration The achieved mass accuracy was typically 30 keV which represents an improvement by a factor of 3 compared to our former experiments [1,2] In addition, the masses of 139 nuclides were indirectly determined by means of known decay energies (α, β or proton) The masses of 114 nuclides were obtained for the first time [8] The measured masses cover a large area of neutron-deficient nuclides from krypton to uranium

Our experimental results have been compared with 77 mass values measured at ISOLTRAP Both results are in excellent agreement characterized by a reduced χ^2 = 1 12 [8]

The precise location of the proton dripline (S_p = 0) was determined for all odd-Z elements from terbium to protactinium [2,8] Moreover, from our results the two-proton dripline (S_{2p} = 0) was identified for mercury, thallium, lead and bismuth elements [8]

The predictions of different mass models were tested over a large part of the nuclidic chart consisting of 310 masses which were not included in the parameter adjustments of these models (see Fig 3) The comparison reveals that presently the mass models cannot reproduce the new masses within an accuracy of 300 keV, e g , the recent Hartree-Fock-Bogoliubov model (HFB) [10] yields a deviation σ_{rms} = 650 keV [8]

The achieved excellent experimental mass accuracy has allowed new investigations of

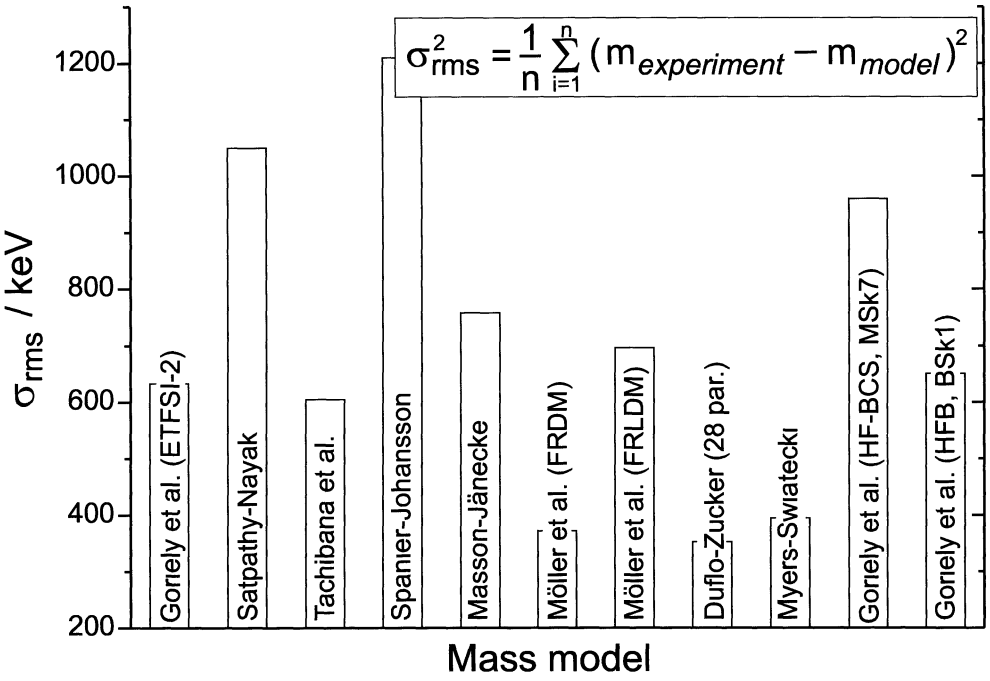

Figure 3 New mass values as a crucial test for the predictive power of mass models The deviations (σ_{rms}) were calculated with 310 masses (n in the formula) which were not experimentally known in the last Atomic Mass Evaluation (AME) [9]

the isospin dependence of nuclear pairing energies We observed that the experimental pairing-gap energies for isotopes from Z=50 to Z=82 increase towards the proton dripline for both, the protons and the neutrons The mass models fail to describe this observed dependence as can be seen, e g for hafnium isotopes in Fig 4 Indications for this experimental trend were first suggested from indirect mass measurements in Ref [11] The BCS formalism within the Finite-Range Liquid Drop Model (FRLDM) [12] was applied to improve the pairing description using the present experimental results The pairing strength G was parameterized with 2 constants for protons (p) and neutrons (n) $G_{p(n)} = g_{0p(n)}/A + g_{1p(n)}(N-Z)/A^2$ and the best agreement with the experiment was obtained with $g_{0p} = g_{0n} = 20\ 80$ MeV and $g_{1p} = -g_{1n} = 22\ 40$ MeV [8] With this pairing description the σ_{rms} value of the FRLDM was reduced by about 130 keV

4 Summary and Outlook

The combination of the FRS-ESR has presented precise mass measurements over a large part of the previously unknown nuclear mass surface These measurements give unique opportunities for studying nuclear structure effects and for testing and improving nuclear theories

Mass measurements of shorter-lived ($T_{1/2} \approx 1$ s) nuclides are planned in future experi-

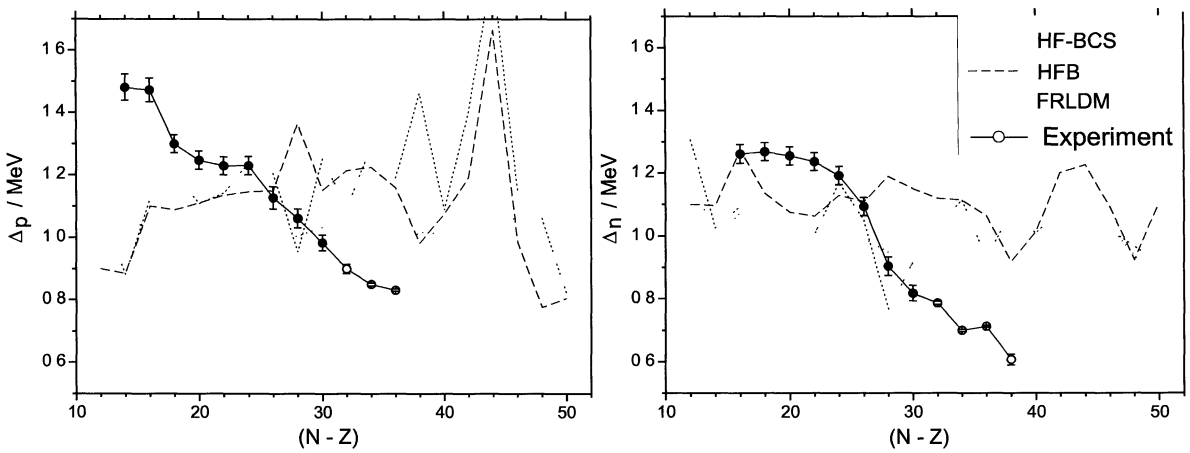

Figure 4 Comparison of the proton (left panel) and neutron (right panel) pairing-gap energies for even-even hafnium isotopes derived with the 5-mass formula from experimental mass values and from predictions of mass models [10,12] The experimental values are taken from this work and Ref [9] The full symbols represent the new experimental values

ments with a combination of stochastic and electron cooling and the use of a faster system with a resonant Schottky pick-up probe

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