Direct Mass Measurements of Stored Exotic Nuclei

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1 Time-resolved Schottky Mass Spectrometry

The analysis of the data from the experimental run on direct mass measurements of bismuth projectile fragments with the time-resolved Schottky Mass Spectrometry (SMS) is completed [1]. Experiment and analysis were described in previous reports [2, 3]. Here we report on some extracted results. For more details see [4, 5].

583 different nuclides were identified 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 as compared to our former experiments [6, 7]. 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 [1]. The measured masses cover a large area of neutron-deficient nuclides from krypton to uranium. The data were included in the latest Atomic Mass Evaluation (AME) [8].

Our experimental results have been compared with 77 mass values measured at ISOLTRAP. Both results are in excellent agreement characterized by a reduced $\chi^2 = 1.12$ [1]. As an example, the comparison of our measured data with the corresponding measurements at ISOLTRAP of [9] is demonstrated in Figure 1 where both shown as deviations to AME [10]. Note, that uncertainties of AME are not shown in the figure.

The precise location of the proton dripline ($S_p = 0$) was determined for all odd-Z elements from terbium to protactinium [1, 7]. Moreover, from our results the two-proton dripline ($S_{2p} = 0$) was identified for mercury, thallium, lead and bismuth elements [1].

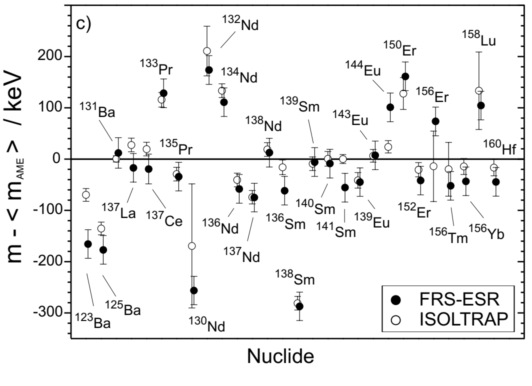

Figure 1: The measured data from our SMS experiment and from ISOLTRAP [9] are both compared with the prediction of the AME table [10].

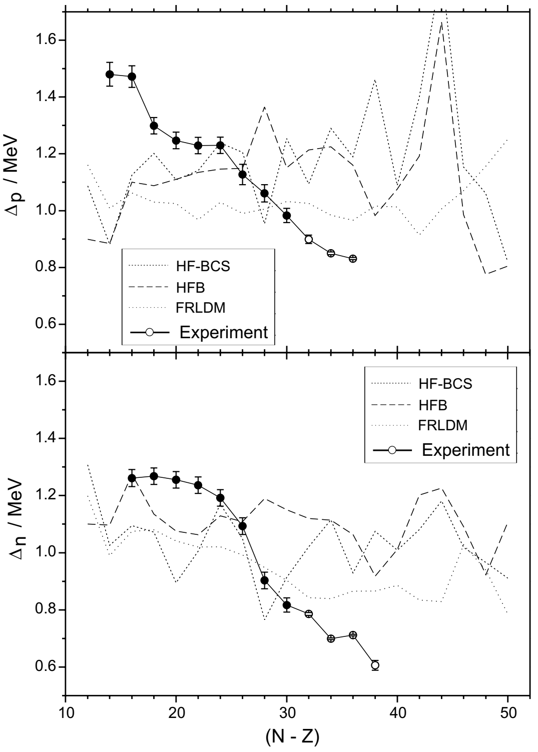

Figure 2: Comparison of the proton (upper panel) and neutron (lower panel) pairing-gap energies for even-even hafnium isotopes derived with the 5-mass formula [12] from experimental mass values and from predictions of mass models [11, 15]. The experimental values are taken from this work and Ref. [10]. The full symbols represent the new experimental values.

The achieved excellent experimental mass accuracy has allowed new investigations of 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. Current mass models fail to describe this observed dependence as can be seen, e.g. for hafnium isotopes in Figure 2. Indications for this experimental trend were first suggested from indirect mass measurements in Refs. [13, 14]. With our new data systematic investigations are possible. The BCS formalism within the

Finite-Range Liquid Drop Model (FRLDM) [15] 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 [1]. With this pairing description the σ_{rms} value of the FRLDM was reduced by about 130 keV.

Presently the analysis of the experimental run dedicated to mass measurements of neutron-rich uranium projectile fragments is underway.

2 Isochronous Mass Spectrometry

Isochronous Mass Spectrometry (IMS) [16] was used for the first time with uranium fission fragments [17]. Masses of 41 short-lived neutron-rich nuclides in the element range of $32 \leq Z \leq 57$ were measured for the first time [18]. A mass resolving power of 2×10^5 (FWHM) was achieved with a typical uncertainty of about $2{\times}10^{-6}$.

The new masses belong to very exotic nuclides close to the astrophysical r-process path. Thus, they are of great importance for testing the predictive power of current mass models which are extensively used for astrophysical calculations.

We present an example of measured masses for neutron-rich Pd and Te isotopes compared with theoretical predictions in Figure 3. Even this small subset of the new data indicates large deviations from the theories (HFB [11], HF+BCS [11], FRDM [15]) and from AME extrapolation [10].

The qualitative comparison of the predictive powers for various mass models and relations is listed in Table 1 [18]. The average deviation σ_{th} of the model from experimental data is defined by the equation

$$\frac{1}{n-1}\sum_{i=1}^{n}\frac{(m_{exp}-m_{th})_i^2}{(\sigma_{exp})_i^2+\sigma_{th}^2} = 1. \qquad (1)$$

The value σ_{th} should be close to the rms–deviation

$$\sigma_{rms}^2 = \frac{1}{n}\sum_{i=1}^{n}(m_{exp}-m_{th})_i^2 \qquad (2)$$

if the experimental errors are less than the theoretical errors. Index n in both formulas runs over all newly measured masses. Comparison of the σ_{th} values with the corresponding rms-deviations indicates that the theoretical uncertainties clearly exceed the experimental ones. In general, the predictive power is higher if the theoretical models were adjusted to a larger area, what is not the case for the calculations collected in [19]. On the other hand the smooth extrapolation by [8] uses the most recent mass values. The fully self–consistent model using the Hartree–Fock–Bogoliubov method [11] seems to be the most successful one.

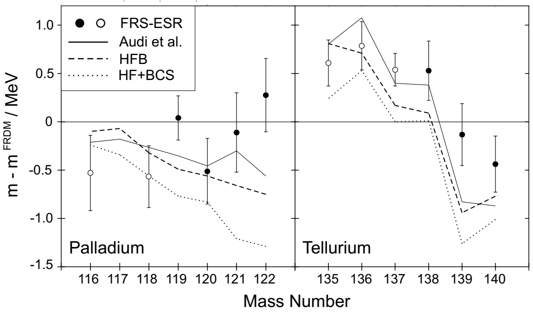

Figure 3: Preliminary experimental data of new masses for Te and Pd isotopes compared with the AME prediction [10] and with theories (HFB[11], HF+BCS[11], FRDM[15]). Masses measured for the first time are indicated by full circles. The open circles represent our values for nuclides with previously known masses.

Mass formula	$\sigma_{rms}[keV]$	$\sigma_{th}[keV]$
Tachibana et al. [19]	935	877
Satpathy–Nayak [19]	1274	1227
Masson–Jänecke [19]	1002	956
FRLDM [15]	607	537
FRDM [15]	667	578
HFB with BSk2 [11]	575	491
HF+BCS with MSk7 [11]	784	714
ETFSI with SkSC18 [20]	657	578
Myers–Świątecki [21]	673	612
Duflo–Zuker (10 par.) [22]	826	765
Duflo–Zuker (28 par.) [22]	683	610
Comay–Kelson–Zidon [19]	801	733
Jänecke–Masson [19]	1186	1133
Audi et al. [8]	651	573

Table 1: Predictive power of various mass models. The rms–deviation σ_{rms} of the model from experimental data is obtained from Eq. 2, theoretical deviation σ_{th} from Eq. 1

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