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Effects of the pairing energy on nuclear charge radii

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Abstract. Atomic masses of various radionuclides around the $Z = 82$ shell closure were determined with the ISOLTRAP mass spectrometer. This particular mass region is characterized by strong nuclear structure effects, like, *e.g.*, shape coexistence. In this contribution results derived from mass spectrometry and laser spectroscopy are examined for a possible correlation between mass values and nuclear charge radii.

PACS. 07.75.+h Mass spectrometers – 21.10.Dr Binding energies and masses – 27.80.+w $190 \leq A \leq 219$

1 Experimental mass determination

The triple trap mass spectrometer ISOLTRAP [1,2,3] allows for the precise mass determination of exotic nuclides far from stability with uncertainties $\delta m/m$ of about 10^{-8} [4]. The mass of an ion stored in a strong magnetic field of a Penning trap is determined via a measurement of its cyclotron frequency $\nu_c = qB/(2\pi m)$, where B denotes the magnetic field strength. In order to calibrate the magnetic field during a measurement, the cyclotron frequency of a reference nuclide with precisely known mass value is determined in regular time intervals. From the obtained frequency ratio $r = \nu_{c,\text{ref}}/\nu_c$ the mass of the nuclide to be studied is deduced.

The region around the $Z = 82$ shell closure is of huge interest for the study of nuclear structure effects. Those reveal themselves for example at the neutron-deficient side as an odd-even staggering effect in nuclear charge radii [5] and in the observation of triple shape coexistence in the case of ^{186}Pb [6]. Recent mass measurements on neutron-deficient as well as on some neutron-rich isotopes of thallium, lead, bismuth, francium, and radium were carried out with the ISOLTRAP mass spectrometer [7]. In this region one of the main experimental challenges is the existence of two or even three isomeric states with low excitation energies. Since these are less than 100 keV for particular candidates, a high resolving power $R = \nu_c/\Delta\nu_{c,\text{FWHM}} = m/\Delta m$ of up to 10^7 is required during a measurement. It is determined by the observation time and therefore finally limited by the half-life of the nuclide. Table 1 shows a list of nuclides studied with the ISOLTRAP mass spectrometer in July 2002. For most of these nuclides the deduced mass values could be assigned to a particular isomeric state. Such nuclides, where the resolving power was not sufficiently high to resolve an eventually present contamination of isomeric states are denoted by an "x".

Table 1. Radionuclides studied with the ISOLTRAP mass spectrometer in July 2002. x: a possible contamination was not resolved.

Element	Mass number A
Tl	181, 183, 186m, 187x, 196m
Pb	187, 187m, 197m
Bi	190x, 191, 192m, 193, 194m, 195, 196m, 197x, 215, 216
Fr	203, 205, 229
Ra	214, 229, 230

Due to the extensive studies of the ISOLTRAP mass spectrometer using carbon clusters, errors like, *e.g.*, the mass-dependent systematic frequency shift and the residual systematic uncertainty could be quantified [4]. With a new upper limit $(\delta r/r)_{\text{res}} \leq 8 \times 10^{-9}$, the average uncertainty in the determination of frequency ratios obtained in these data is $(\delta r/r)_{\text{avg}} = 7.5 \times 10^{-8}$. This leads to an average error of $\delta m_{\text{avg}} = 13$ keV in this mass determination in the range of $A = 181$–230. Figure 1 shows a comparison of some of the ISOLTRAP deduced mass values to a compilation of the AME in 2002 [8]. A detailed description of the data analysis and the isomeric assignment will be published elsewhere.

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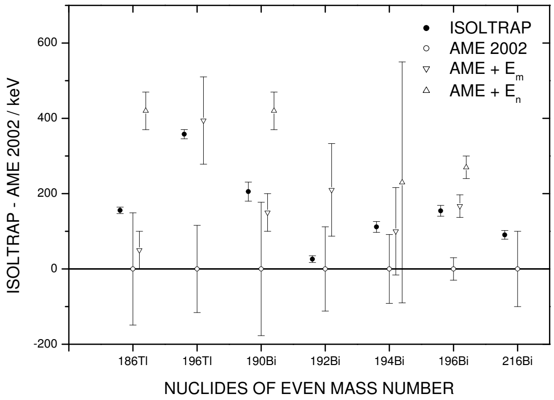

Fig. 1. Comparison of ISOLTRAP mass data for some odd-odd nuclei to a compilation of the AME in 2002 [8]. The zero line represents the AME ground-state mass values. Excited isomers are depicted as open triangles, whereas Em and En are the energies of the first and second excited isomers, respectively.

2 Comparison to nuclear charge radii

This work was already initiated by mass spectroscopic results on neutron-deficient mercury isotopes [9]. The appearance of shape coexistence as observed in the large odd-even staggering of the mercury nuclear charge radii near the $N = 104$ mid-shell region was explained by the size of the neutron pairing energy. As this quantity has an absolute value of only about 1 MeV, mass data available at that time were of insufficient precision for any analysis. First, the high resolving power $m/\Delta m$ of up to 10^7 of the ISOLTRAP Penning trap mass spectrometer can resolve isomeric states. Secondly, the recently demonstrated mass uncertainty of $\delta m/m < 10^{-7}$ helps to analyze the nuclear fine structure in the neutron-deficient thallium, lead, and bismuth isotopes. New results of laser spectroscopic studies are available for neutron-deficient lead isotopes [10] which will be compared with the lead masses, in an upcoming work. The systematic comparison of the neutron pairing gap energies

$$\Delta^3(N) = \frac{(-1)^N}{2}\left[B(N-1) + B(N+1) - 2B(N)\right], \quad (1)$$

$$\Delta^4(N) = \frac{1}{2}\left[\Delta^3(N) + \Delta^3(N-1)\right] \quad (2)$$

to the behavior of the nuclear mean square charge radii $\delta\langle r^2\rangle$ (data from [5,11]) is used to search for a possible correlation. Figure 2 shows the examples of mercury- and thallium-isotopes. In $\Delta^3(N)$ and $\Delta^4(N)$, which are deduced as the second derivative of the nuclear binding energy along an isotopic chain, the shell closure at $N = 126$ is visible as a maximum. This difference in binding energy of the last neutron represents the size of the n-n interaction strength. In addition, a decrease of the interaction strength is observed around the mid neutron shell $N = 104$. Its position coincides with those isotopes that show the characteristic staggering effects. This strengthens the idea that the size of the n-n pairing is responsible for the stabilization of a weakly deformed shape. At mid-shell, the pairing energy is diminished in comparison to the general trend, and a more deformed shape appears. The systematic study of these fine correlations has become possible due to the high precision of the new ISOLTRAP data.

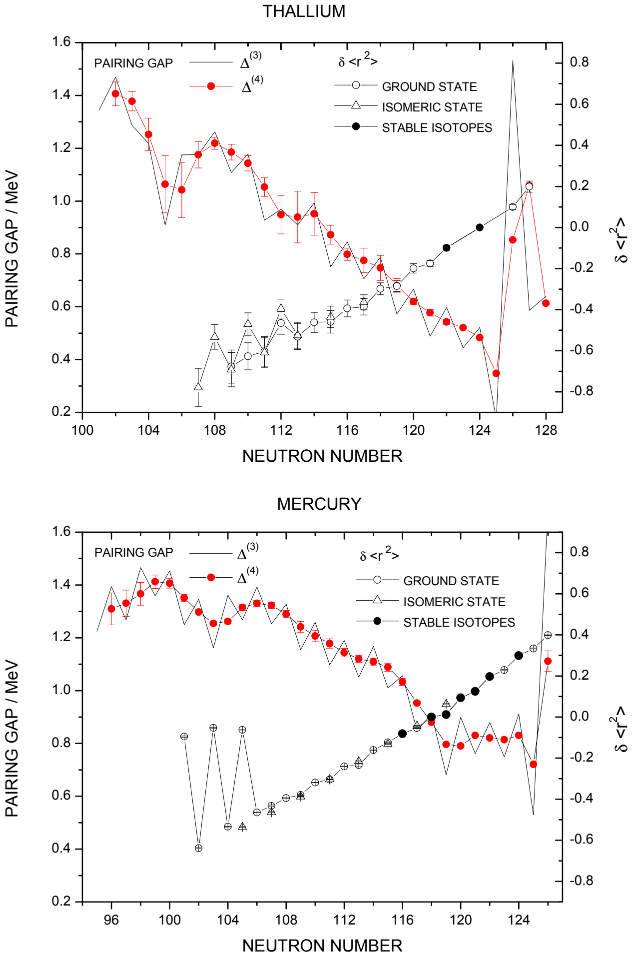

Fig. 2. Comparison of neutron pairing gap energies $\Delta^{(3)}$, $\Delta^{(4)}$ to nuclear mean square charge radii $\delta\langle r^2\rangle$. Note that in thallium the radii of the isomer exhibit the staggering behavior. $\delta\langle r^2\rangle$ error bars for mercury are drawn within the symbol.

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