Synergy of decay spectroscopy and mass spectrometry for the study of exotic nuclides

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Motivation

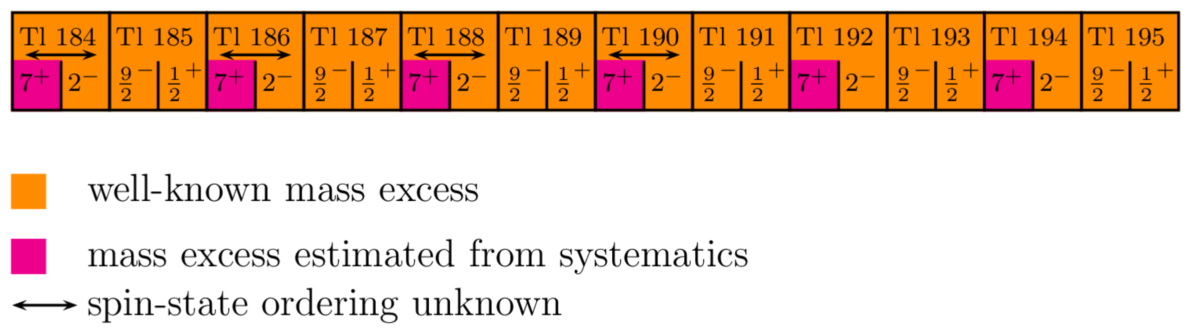
With only two ingredients, atomic nuclei exhibit a rich structure depending on the ordering of proton- and neutron-occupied states. This ordering can give rise to isomers – excited states with exceptional long half-lives ($t_{1/2}$>1ns) compared to other excited states in the nucleus – especially in the vicinity of shell closures. On-line mass measurements can often be compromised by the existence of such states that may even be produced in a higher proportion than the ground state.

At the high-precision Penning-trap mass spectrometer ISOLTRAP, which can resolve and remove even isomeric states at only a few 100 keV, mass measurements can be combined with nuclear decay spectroscopy. This allows to study the decay pattern of the state extracted from the Penning trap and thus to assign the mass to the right state.

Region of Interest

The Tl (Z=81) isotopes miss only one proton to the next magic number. Most of the neutron-deficient Tl isotopes have isomers at low excitation energies (<1MeV). This allows to explain some basic features in the view of the single-particle shell model.

In addition, reports about shape coexistence exist in the neighboring nuclides.



Experimental Setup

The Penning-trap mass spectrometer ISOLTRAP [a] uses quasi-continuous radioactive ion beams from the on-line isotope separator ISOLDE/CERN. To obtain low-energy ion bunches required by the Penning traps the ion beam is buffer-gas cooled and bunched in the radio frequency quadrupole ion trap (1). In the preparation Penning trap (2) further cooling and isobar mass separation is carried out. In the precision Penning trap (3) isomers with a few 100 keV excitation energy can be resolved and removed.

For mass measurements, a resonant RF-excitation of the ion motion in the precision Penning trap is followed by a time-of-flight (TOF) measurement [b] which allows to determine the cyclotron frequency of the ion

$$\omega_c = q * B/m$$

with mass m and charge q in the magnetic field B. If the excitation is in resonance the TOF gets minimal, see inset Fig. 1.

For decay measurements, the purified ion sample is implanted into an aluminized Mylar tape (4). The implantation site lies within a cylindrical plastic scintillator sensitive to emitted β particles. In addition, it is surrounded by up to 2 HPGe detectors for γ detection.

[a] Mukherjee, M. et al., *Eur. Phys. J. A* **35**, 1-29 (2008)

[b] König, M. et al., *Int. J. Mass. Spectrom. Ion. Process* **142**, 95-116 (1995)

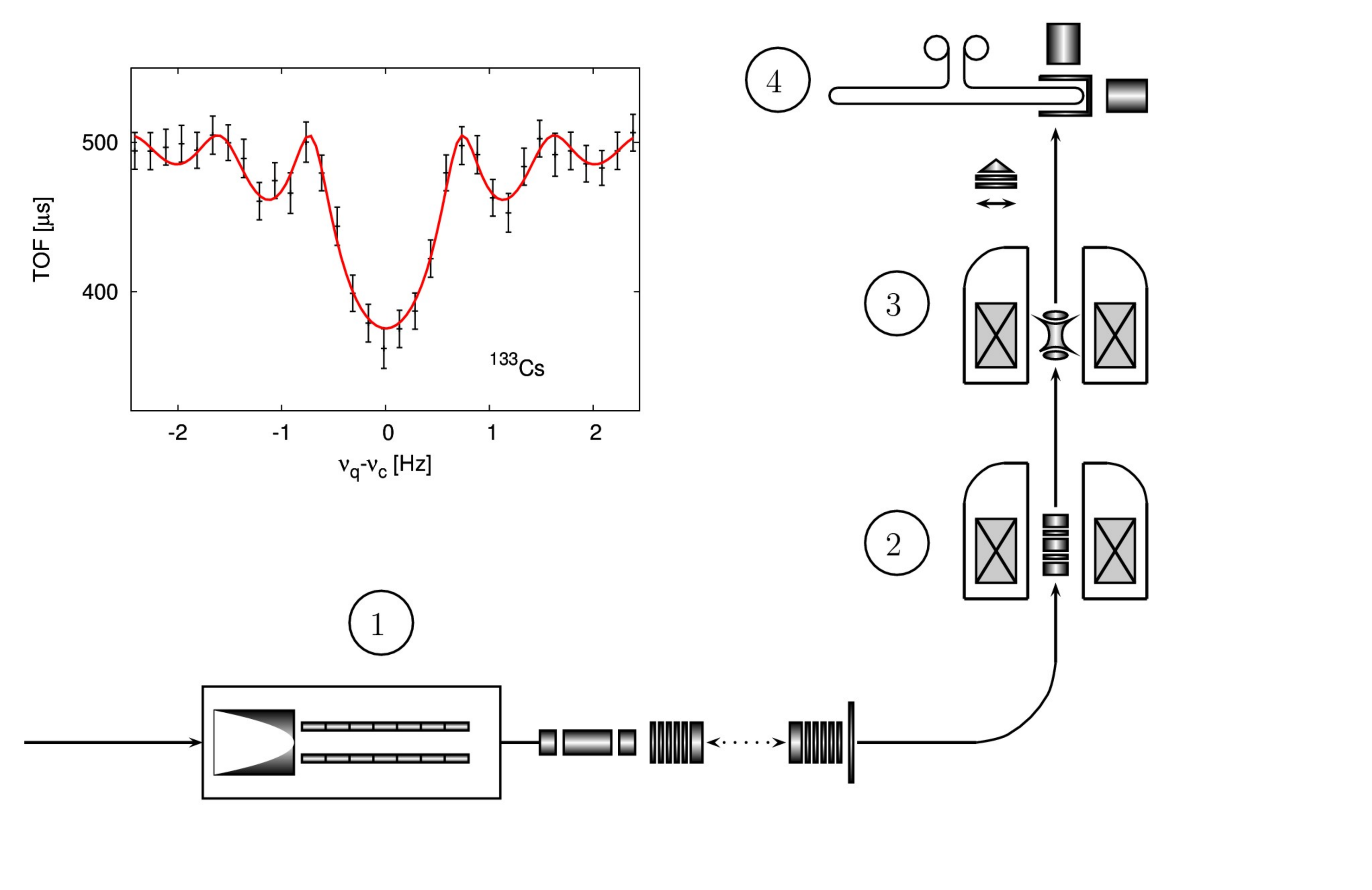


Fig.1: Schematic view of the ISOLTRAP setup and TOF resonance for ^{133}Cs.

Results

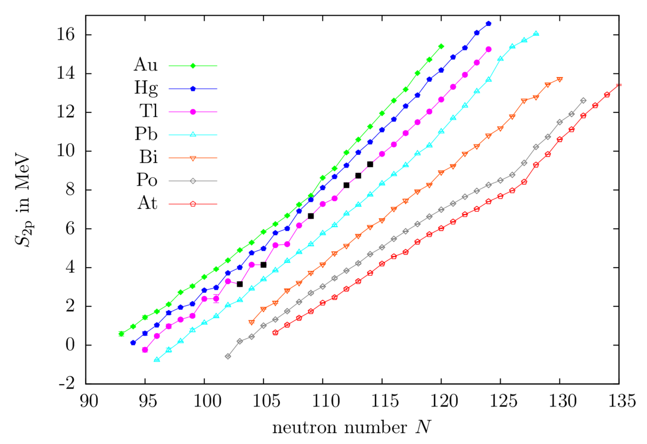


Fig. 2: Odd-even staggering was in the two proton separation energies for neutron-deficient Tl isotopes.

Thallium lies next to Pb and Hg which behave different under the removal of neutrons. While the first remains spherical, an onset of deformation and shape coexistence is observed for the latter for N≤110.

Within two measurement campaigns the isomerism in ^{184,190,193,194,195}Tl was investigated. The uncertainties on the mass values could be reduced up to a factor of 20. This allowed to uncover an odd-even staggering in the two-proton separation energies

$$S_{2p} = B(Z, N) - B(Z - 2, N)$$

for N<112, see Fig. 2. Thanks to the cooperation of the mass and decay measurements a mass-spin-state assignment was possible for ^{190,193,194}Tl. Due to the presence of the ground and isomeric state for ^{194}Tl the excitation energy of the latter was determined for the first time experimentally, see Fig. 3. Systematics of the excitation energies for even-A Tl isotopes support a mixed configuration ($\pi s_{1/2} \bullet \nu p_{3/2} + \pi s_{1/2} \bullet \nu f_{5/2}$) for the 2- state with N<117, see Fig. 4. From the charge radii, see Fig. 5, a deviation from the spherical ground state for N<115 is observed as well as a shape staggering between the ground and isomeric state for odd-A Tl isotopes. Thus, different nuclear properties indicate an onset of deformation in the neutron-deficient Tl isotopes.

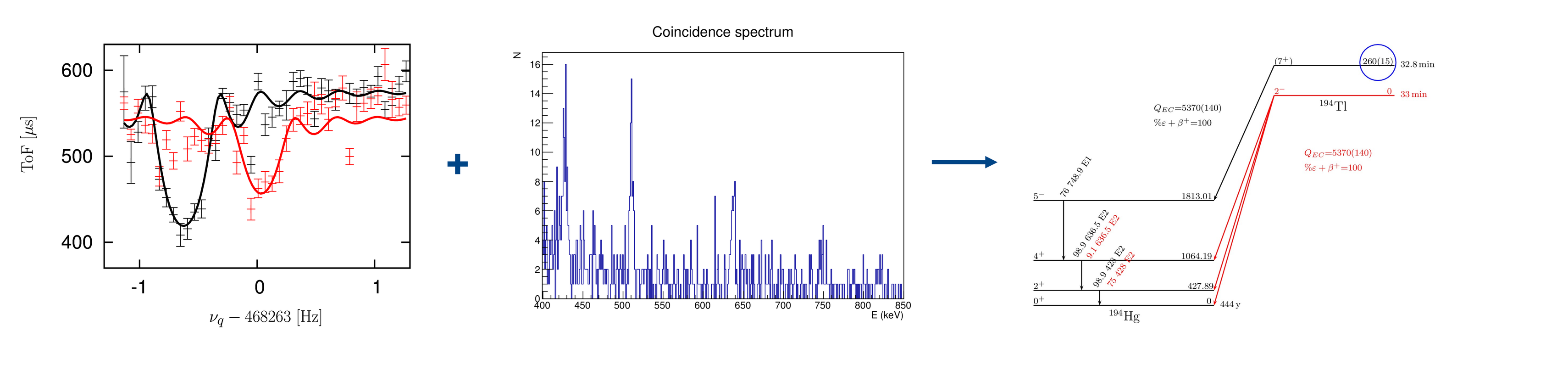


Fig. 3: Combination of mass and decay measurements for a mass-spin-state assignment.

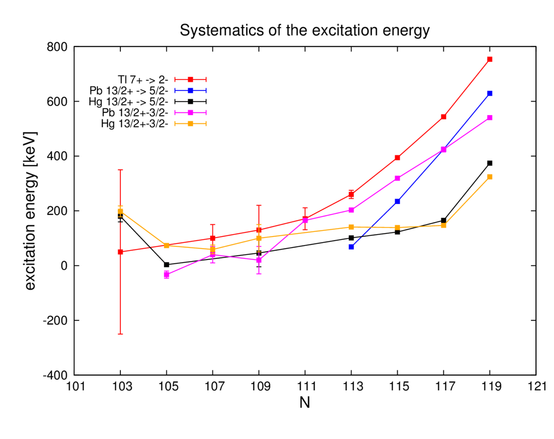


Fig. 4: Excitation energy systematics for even-A Tl isotopes.

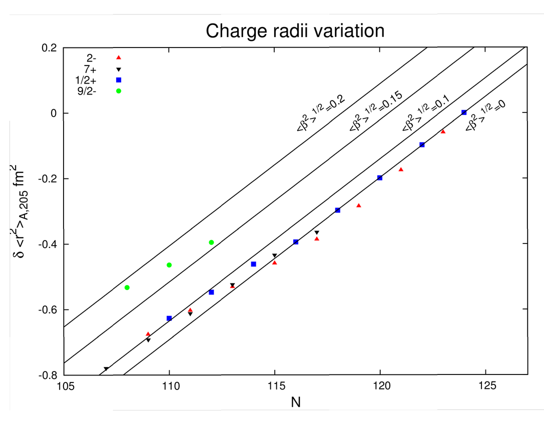


Fig. 5: Root-mean-square charge radii for neutron-deficient Tl isotopes.

Publications

[1] *"IS463: Study on neutron-deficient Tl isotopes"*, J. Stanja, ISOLDE Newsletter (2012)

[2] "*Q Value and Half-Lives for the Double-β-Decay Nuclide ^{110}Pd*", D. Fink et al., Phys. Rev. Lett. **108**, 062502 (2012)

[3] "*On-line separation of short-lived nuclei by a multi-reflection time-of-flight device*", R. N. Wolf et al., Nucl. Inst. and Meth. A **686**, 82-90 (2012)

[4] "*Trap-assisted decay spectroscopy with ISOLTRAP*", M. Kowalska et al., Nucl. Inst. And Meth. A **689**, 102-107 (2012)

[5] "Plumbing neutron stars to new depth with the binding energy of the exotic nuclide ^{82}Zn", R. N. Wolf et al., Phys. Rev. Lett. (accepted for publication)

Collaborations

ISOLTRAP Collaboration (MPI-K Heidelberg, GSI Darmstadt, Katholieke Universiteit Leuven, University of Istanbul, University of Manchester, E.-M.-A.-Universität Greifswald, FAIR, CERN, Université Paris-Sud, RIKEN, TU Dresden)

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DRESDEN concept

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