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THE RECOIL DISTANCE DOPPLER-SHIFT TECHNIQUE: A VALUABLE METHOD FOR NUCLEAR STRUCTURE STUDIES FAR FROM THE VALLEY OF STABILITY*

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Besides the level scheme, absolute transition strengths between excited states yield fundamental information on nuclear structure and can be determined from level lifetimes. The recoil distance Doppler-shift (RDDS) technique is very valuable for the measurement of lifetimes in the picosecond range. During the last years, our group constructed several very compact plunger devices for RDDS experiments with γ-ray spectrometers coupled to charged particle detector arrays situated in the target chamber, and with dedicated setups for multinucleon transfer reactions where the plunger must be placed at the grazing angle of the reaction. Recent investigations have addressed the evolution of nuclear structure in neutron-deficient nuclei in the $A = 170$ mass region from yrast $B(\mathrm{E2})$ values and are discussed in this article. For these investigations very small $B_{4/2} = B(\mathrm{E2}; 4_1^+ \to 2_1^+)/B(\mathrm{E2}; 2_1^+ \to 0_1^+)$ ratios are of particular interest, which cannot be explained with standard collective models and which are not expected from the actual level schemes nor this far from closed shells. Here, we present our new work on ^{168}W, ^{172}Pt, and ^{176}Pt, focus on this $B(\mathrm{E2})$ anomaly, and include $B(\mathrm{E2})$ values between higher yrast states for which experimental data have been sparse.

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1. Development of compact plunger devices for different experimental conditions

For many years, our group has been working on the design and construction of sophisticated plunger devices for different experimental conditions of RDDS measurements [1], *i.e.*, in combination with recoil separators, with compact charged particle detector arrays mounted inside the target chamber, and for multinucleon transfer studies where recoil identification is required at the grazing angle of the respective reaction channel. As an example, Fig. 1 shows a sketch of the compact plunger device APPA (Advanced Plunger-Particle detector Array) that was constructed by our group for RDDS experiments at the University of Jyväskylä, Finland [2]. It is used with the JUROGAM III γ-ray spectrometer [3] coupled to the MARA [4] or RITU [5, 6] separators and the charged-particle veto detector JYTube [2]. A similar device, the iCAPS (integrated Cologne Argonne Plunger Setup) plunger, was built by us for RDDS experiments at the ATLAS facility at Argonne National Laboratory (ANL) with the γ-ray spectrometers Gammasphere [7] and Gretina [8] coupled to the gas-filled separator AGFA [9] or the mass analyzer FMA [10] and the Microball charged-particle detector array [11] that resides inside the target chamber. Further, our group constructed the compact three-foil (one target, two degrader foils) plunger device CoCo-Diff (Cologne Compact Differential plunger) [12] for experiments with the AGATA γ-ray detector array [13] coupled to, *e.g.*, the PRISMA magnetic spectrograph [14] at the Laboratori Nazionali di Legnaro (LNL), Italy, for use especially in multinucleon transfer reactions. The three-foil arrangement allows to measure two distinct level lifetimes simultaneously or the derivative of the decay curve. A two-foil version of the CoCoDiff plunger was used in previous experiments at LNL.

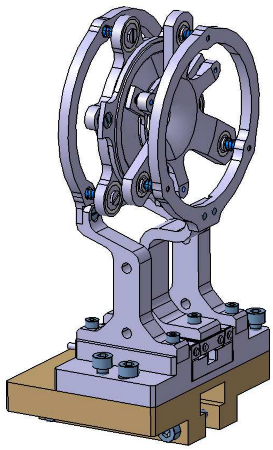

Fig. 1. Sketch of the APPA plunger built for RDDS experiments at the University of Jyväskylä. Its total height is about 60 mm.

2. Structural evolution in neutron-deficient nuclei around $A = 170$

It is well established that shape coexistence of a prolate intruder structure and a weakly deformed, oblate ground-state configuration is present in nuclei around $Z = 82$ and $N = 104$ (neutron mid shell) (see, *e.g.*, [15]). Detailed data on a prolate intruder structure and weakly oblate deformed ground-state configuration exist in neutron-deficient Hg isotopes where the intruding configuration is minimum in energy for ^{182}Hg [15, 16] and results from a $\pi(4p6h)$ excitation across $Z = 82$. In the Pt isotopes around neutron mid shell, the prolate structure even becomes the ground-state configuration [17–21]. From the data on the next lighter Pt isotopes, it seems that the prolate structure increases in energy and a weakly deformed (or quasi-vibrational) structure is associated with the ground-state configuration; the change to a well-deformed rotor appears at low spin [17]. However, theoretical approaches do not yield a conclusive picture, and more experimental data are needed. For example, IBM calculations with configuration mixing and an approach with a Hartree–Fock–Bogoliubov treatment of deformation done for the Pt isotopes with $N \leq 104$ differ drastically from each other [22].

In addition, a B(E2) anomaly was found in Pt, Os, and W isotopes around $N = 92$ [23–26]. The B(E2) values usually increase with spin for the low-lying states of a band structure [27]; *i.e.*, for collective excitations the $B_{4/2} = B(\mathrm{E2}; 4_1^+ \to 2_1^+)/B(\mathrm{E2}; 2_1^+ \to 0_1^+)$ ratio is larger than unity. For an ideal rotor, $B_{4/2} = 1.43$ is expected from the Alaga rules, and for a collective vibrator, $B_{4/2} = 2.0$. $B_{4/2}$ can take values in between those limits, *e.g.*, when using the IBM with dynamical symmetry breaking. This applies for, *e.g.*, ^{178}Pt with $B_{4/2}(^{178}\mathrm{Pt}) = 1.81(15)$ [20]. However, for more neutron deficient isotopes, a B(E2) anomaly frequently appears represented by small such ratios: $B_{4/2}(^{168}\mathrm{Os}) = 0.34(18)$ [23], $B_{4/2}(^{170}\mathrm{Os}) = 0.38(11)$ [24], $B_{4/2}(^{166}\mathrm{W}) = 0.33(5)$ [25], and $B_{4/2}(^{172}\mathrm{Pt}) = 0.55(19)$ [26]. It should be stressed that the 2_1^+ states of these nuclei agree with the expected correlations between the $R_{4/2} = E(4_1^+)/E(2_1^+)$ ratio and the $B(E2; 2_1^+ \to 0_1^+)$ values [28]. In the present understanding of nuclear structure, the only possible exceptions from $B_{4/2} > 1$ are excitations exhibiting seniority symmetry. These are only expected near magic numbers, but there is no corresponding experimental evidence in this region. Perhaps shape coexisting structures are causing $B_{4/2} < 1$, but there are no such cases known so far. On the other hand, recently, in this region $B_{4/2} < 1$ could be calculated within an extension of the consistent-Q IBM Hamiltonian and explained to originate from a strong band mixing induced by a third-order term of the triaxial rotor realization [29]. Furthermore, even more recently in a follow up publication [30], a general procedure for constructing triaxial rotor modes in the IBM was demonstrated and the collective mechanism underlying the $B(E2)$ anomaly phenomena was elucidated.

Data on E2 transition strengths between higher-lying yrast states in nuclei in this region are very sparse and, thus, the structural evolution along the yrast line is unclear. Therefore, in this work, we investigated ^{172,176}Pt and ^{168}W with the RDDS technique aiming at the measurement of yrast B(E2) values at least up to the 8_1^+ states. For ^{172}Pt, only the lifetimes of the 2_1^+ and 4_1^+ states are known from an RDDS study using γ-ray "singles" spectra tagged by α-decay [26]. The yrast B(E2) values in ^{176}Pt stem from older work [17] and the lifetime values might be affected by unobserved delayed side feeding, motivating a new study using $\gamma\gamma$ coincidences to rule out such effects. In ^{168}W, lifetimes were measured for several states in an older work [31], too, using γ-ray "singles" spectra employing only a multiplicity filter to reduce contamination from Coulomb excitation of the target and activity. Thus, corrections for unobserved delayed feeding had to be taken into account. Therefore, the results might be affected by additional unobserved feeding. Furthermore, for the 6_1^+ and 8_1^+ states only upper limits of the lifetimes were measured in [31]. This motivates a new investigation of ^{168}W with $\gamma\gamma$ coincidences.

Lifetimes in ^{172}Pt were measured in our study at ANL with the RDDS technique using the ^{92}Mo(^{83}Kr, $3n$)^{172}Pt fusion–evaporation reaction and combining the iCAPS plunger with Gammasphere and AGFA. The latter enabled ^{172}Pt identification via α-decay tagging, which was required due to the very small production cross section for ^{172}Pt of about 10^{-5} of the total reaction cross section. The experiment was very similar to the earlier one by Cederwall and coworkers that was performed at the University of Jyväskylä [26]. The measurement was done at eight target–degrader distances ranging from nearly electrical contact of the foils up to 400 μm.

The investigation of ^{176}Pt was done at the Heavy Ion Laboratory (HIL), University of Warsaw, Poland, with the Cologne coincidence plunger device [1] mounted at the EAGLE γ-ray spectrometer [32], using the ^{148}Sm (^{32}S, $4n$)^{176}Pt fusion–evaporation reaction and analyzing $\gamma\gamma$ coincidences with gates on flight components of feeding transitions of the levels of interest to rule out any contribution from unobserved delayed feeding.

Figure 2 depicts the transition quadrupole moments $Q_{\rm t}$ within the yrast bands of ^{172}Pt and ^{176}Pt determined from level lifetimes from the preliminary analysis of our data. These are compared to the predictions for vibrator and rotor cases as well as for the X(5) critical point of the transition between those symmetries and to the results for ^{178,180}Pt from [20, 21]. The 2_1^+ and 4_1^+ states in ^{176}Pt show a similar degree of collectivity as those in ^{178,180}Pt, and the $Q_{\rm t}$ values are consistent with a rotor. A drastic change takes place in ^{172}Pt where the collectivity is far lower. The related E2 transition strengths are about a factor of ten lower as compared to ^{176}Pt. Thus, the lowest states in ^{172}Pt might belong to a weakly deformed configuration. However, due to the large error bars of the preliminary results from this work, the resulting $B_{4/2}$ ratio is compatible with both previous data [26] as well as with collective models.

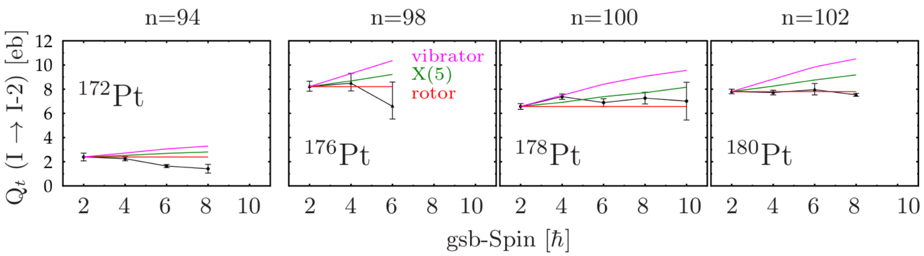

Fig. 2. (Colour on-line) Transition quadrupole moments between yrast states in ^{172}Pt, ^{176}Pt (preliminary data from this work), and ^{178}Pt [20] and ^{180}Pt [21]. The lines in the respective diagrams are drawn to guide the eye, where the upper line (magenta) represents the expectation values for a vibrator nucleus, the middle one (green) that for an X(5) nucleus, and the lower one (red) that for a rotor nucleus.

The nucleus ^{168}W was investigated at ANL with the Cologne coincidence plunger and Gammasphere using the $^{108}\mathrm{Pd}(^{64}\mathrm{Zn}, 2p2n)^{168}$W fusion–evaporation reaction. The experiment was done at 12 target–stopper distances from nearby electrical contact of the foils up to 6400 μm. The lifetimes of the 2_1^+, 4_1^+ and 6_1^+ states were measured, with the preliminary result $B_{4/2}(^{168}\mathrm{W}) = 0.91(8)$. From the $B_{4/2}$ ratio, this nucleus is just at the transition towards the region where the B(E2) anomaly was found. The value derived from the literature, $B_{4/2}^{\mathrm{old}}(^{168}\mathrm{W}) = 1.11(33)$ [31], did due to its large uncertainty not allow to exclude agreement with the value for a rotor, whereas our new result does. Furthermore, for the first time, the 6_1^+ lifetime has been measured yielding a very small $B_{6/2} = B(\mathrm{E2}; 6_1^+ \to 4_1^+)/B(\mathrm{E2}; 2_1^+ \to 0_1^+)$ ratio of $B_{6/2}(^{168}\mathrm{W}) = 0.34(3)$. Within the aforementioned recent theoretical works on the B(E2) anomaly in neutron-deficient even–even nuclei in the $A \approx 170$ mass region [29, 30] these low $B_{4/2}$ and $B_{6/2}$ ratios can be interpreted for the first time with triaxial modes in the IBM and a strong band mixing.

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