論文審査の結果の要旨

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Mr. Yokoyama's thesis entitled "Shape evolution in neutron-rich midshell nuclei studied by γ-ray spectroscopy" consists of six chapters. After an introduction to the phenomenon of nuclear deformation in the first chapter, the second chapter describes the experimental setup and conditions. Chapter 3 is devoted to the analysis procedure, including calibration and correction steps. The results on half-lives and level schemes of nuclei are discussed in chapter 4. This is followed by a discussion of the results and comparison to systematics and theoretical models. The thesis concludes with a chapter summarizing the findings. In the appendix Mr. Yokoyama describes the basics of the deformed shell model, defines Weisskopf transition probabilities and hindrance factors. He also presents the spectra and decay curves of several other nuclei that have been observed, and are not yet described in the main part.

The objective of the thesis is to study the evolution of deformation in nuclei around proton number $Z \sim 60$ and neutron number $N \sim 100$. In addition to the well-known quadrupole deformation, in this region theoretical calculations predict the occurrence of higher order terms, such as octupole and hexadecupole, in the nuclear deformation. In this thesis nuclei around $A \sim 160$ have been studied using isomeric and β-decays. The very neutron-rich nuclei under investigation can only be produced using fission and fragmentation reactions at radioactive beam facilities. The thesis describes two experiments that have been carried out at the Radioactive Ion Beam Factory (RIBF) in Japan. This state-of-the-art facility is the only place in the world where such exotic nuclei can be produced. Due to the production mechanism, in-flight fission, the resulting ion beam is not pure, and a separator has to be employed in order to filter out the ions of interest. The setup of the BigRIPS at RIBF is described in great detail in the thesis. The analysis of data taken by the beam line detectors for timing and position measurement and energy loss in addition to the magnetic field strength of the dipole magnets allows to identify the ions passing through on an event-by-event basis. $B\rho$, ΔE and the time-of-flight yield the nuclear charge Z and the mass to charge ratio A/q leading to a unique identification of each beam particle. After separation and identification the nuclei are stopped and one waits for their decay. In the work presented in this thesis, two setups were used. The first consists of a passive stopper, surrounded by clover-type germanium γ-ray detectors optimized for isomer spectroscopy. The other setup uses an active stopper, to correlate the position of implantation with the position of a β-decay event. The γ detector of choice in this setup is the EURICA array.

In the thesis the different analysis steps are described in great detail. After sorting and purification of the data, energy and efficiency calibrations are performed. For the EURICA array a simple add-back procedure is included to add to the efficiency. For coincidence measurements, additionally the time of events has to be measured to correlate them. Using the time difference between implantation and decay, the half-lives for isomeric and β decay can be determined. For β decays the additional correlation of the implantation position in the active stopper and the detection of the electron from the β decay is used to drastically reduce the background.

Within the work presented in the thesis a large number of new results have been obtained. 22 new isomers have been observed between Pr ($Z = 59$) and Ho ($Z = 67$). The analysis concentrated on the even-even nuclei with $N = 98$ and 100 to systematically study the evolution of K-isomers and low-lying excitations along the isotopic and isotonic chains. Lifetimes of isomeric states are obtained by gating on delayed γ-ray transitions after implantation. The level schemes are constructed from γ-γ coincidences. Based on comparison with systematics, spins and parities are assigned to low-lying states. The spin and parity of isomeric states are assigned based on the decay pattern to the ground state band. Convincing evidence for the proposed level schemes is presented in the thesis. In addition to isomer spectroscopy nuclei have been investigated by β-decay. The main focus of the analysis is the decay of ^{150}Cs to ^{150}Ba, the heaviest Ba isotope observed. The half-life of ^{150}Cs has been obtained by fitting the time distribution of detected β events after the implantation with a curve containing the main decay, ^{150}Cs to ^{150}Ba, as well as all subsequent daughter decays. Two γ-rays have been observed after the β decay, due to low statistics a log likely-hood analysis was performed to test the significance of the observed peaks. Spin and parity assignments are based on comparison with neighboring nuclei. The description of the data analysis steps is sound, and arguments for the placement of transitions and levels are well presented.

In chapter 5 the results are discussed, first the evolution of 2^+ and 4^+ states in even-even nuclei is investigated. From the newly determined excitation energies the moment of inertia of the nucleus can be calculated assuming a rotor model. Moments of inertia and energy ratios are a good indicator for the deformation of the nucleus. For the nuclei investigated within this thesis, the rotational model is applicable, as demonstrated by the measured excitation energies. Previous experiments and theoretical calculations indicated a minimum in the moment of inertia for ^{164}Gd at $N = 100$, indicating a deformed shell-gap there. In this work the systematics is expanded to the Sm and Nd isotopes. A minimum at $N = 100$ is found for Sm but not for Nd. The Nd isotopes also show the largest deformation as indicated by the moment of inertia, however this is not predicted by theoretical calculations. A possible explanation for the disappearance of the deformed $N = 100$ gap is presented in the thesis. Below $Z = 62$ single-particle levels with high n_z quantum number in the Nilsson scheme are filled. Such orbitals contribute to a positive hexadecupole moment. Above Nd negative contributions to the hexadecupole moment set in leading to a reduced moment. The interaction with the neutron orbitals lowers the respective orbits with large n_z. At $N = 100$ this causes the reduction of the gap. Further evidence is presented by the moments of inertia of odd Z nuclei. The second topic is the systematics of K isomers. $K^\pi = 4^-$ isomers have been observed in the $N = 100$ isotopes of Gd, Sm and Nd, they are assumed to be built on a $\nu 7/2[633] \otimes \nu 1/2[521]$ quasi-particle configuration. The gap between these two orbitals decreases as deformation is increased, explaining the reduction in excitation energy for the $K^\pi = 4^-$ isomers from Yb ($Z = 70$) and Sm ($Z = 62$). In Nd however the excitation energy suddenly rises again, this cannot be explained by quadrupole deformation alone. Calculations including hexadecupole deformation show that the quasi-particle energies are very sensitive to the hexadecupole deformation, providing an explanation for the increase of the $K^\pi = 4^-$ isomer excitation energy in ^{160}Nd. Together the results can be interpreted consistently invoking hexadecupole deformation for Nd isotopes around $N = 100$. The last part of the discussion is devoted to the study of octupole collectivity in Ba isotopes. The experimentally observed γ-ray transitions led to a candidate $J^\pi = 3^-$ state at 697 keV in ^{150}Ba, the lowest 3^- state along the chain. Theoretical calculations are presented which show that octupole collectivity is indeed expected to play a major role in ^{150}Ba, however the status of experimental data does not yet allow to make conclusions.

At the end a summary and outlook is presented. Interestingly in the work no isomers have been observed below $Z = 58$. The origin is unclear, but a possible explanation would be the disappearance of deformation or triaxiality. More experiments are suggested. On the other hand the work presented in this thesis is entirely based on the excitation energies of states. Other complementary observables are needed to make more reliable conclusions. Quadrupole deformations can be obtained from lifetime measurements, due to the low excitation energy, and the level of statistics fast timing measurements were not possible in this work. Low-energy Coulomb excitation will provide a measurement of electro-magnetic matrix elements. These give direct information on B(E2) values and therefore lifetimes as well as quadrupole moments. Even higher moments can be extracted through measurements of E3 and E4 transitions. Application of these techniques to the nuclei studied in this thesis is not possible so far, higher beam intensities and new facilities are required.

Mr. Yokoyama's contributions to this work are ubiquitous. He was involved in the entire preparation and execution of two experiments. He was responsible for the setup and calibration of Ge detectors. For the secondary beam production he estimated and optimized the production rates, decided on the different beam settings and participated in the beam tuning. He was in charge of the online analysis of both experiments, which includes beam reconstruction, particle identification, monitoring the data integrity and online search for new isomers and excited states. The offline analysis was his own responsibility, he performed energy and efficiency calibrations, Monte-Carlo simulations and consistency check with known nuclei. Furthermore he analyzed the active stopper and determined the implantation point for β-decay studies. From the data he extracted lifetimes of isomeric states and β-decay half-lives. He also determined the level schemes based on intensity and energy balances as well as coincidence analysis. He led the discussion and investigation of the results of the shape evolution in the $N \sim 100$ nuclei based on the combination of the new results of the two experiments. The amount of new information is remarkable, the data analysis has been performed with great care. The interpretation of the results based on higher order deformation effects is sound, yet careful not to excluded other possibilities. The thesis presented satisfies all aspects of a scientific work.

We therefore conclude that the doctoral degree should be awarded to Mr. Yokoyama.