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Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Implementing the recoil distance Doppler-shift technique at HIE-ISOLDE: Investigation of neutron-rich ^{86}Se

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Abstract: The recoil distance Doppler-shift method (RDDS) is a very valuable technique for measuring lifetimes of excited nuclear states in the picosecond range to deduce absolute transition strengths between nuclear excitations independent on the reaction mechanism. Therefore, we propose an experiment on the N=52 nucleus ^{86}Se with Coulomb excitation in inverse kinematics to implement this method at HIE-ISOLDE using a new plunger device that will be developed and built by our Cologne group for a first RDDS measurements in combination with MINIBALL.

In the region of neutron-rich nuclei nearby N=50 the question arises whether the magic nucleon numbers survive at large values of the isospin. Existing experimental results in this region indicate a weakening of the N=50 shell gap towards Ge (Z=32) and an increase in the region of Zn. Our experiment aims to prove this observation by a measurement of absolute $E2$ transition strengths in ^{86}Se which, in addition, enables to test model predictions in the shell model, the interacting boson model and collective models. Such were already applied to heavier nuclei in this region allowing a detailed interpretation of the structure regarding the evolution of collective phenomena in and proton subshell closures for Sr and Zr isotopes near N=50 and their disappearance for these isotopes more far from N=50.

Requested shifts: 27 shifts
Installation: MINIBALL + CD + plunger

1 Scientific motivation

The evolution of the shell structure of nuclei with extreme numbers of excess neutrons is a field of increasing importance during the last years due to the availability of radioactive beams with sufficient intensities for experimental investigations of such regions. Here we want to focus on the region around the N=50 shell closure that represents a rich laboratory for such studies. In several nuclei close to N=50 collective characteristics were found (see, e.g., [1]). Single particle degrees of freedom play the important role as the N=50 shell closure is reached. Particle-hole states in the fp shell $(2p_{3/2}, 1f_{5/2}, 2p_{1/2})$, as well as the $1g_{9/2}$ orbital for protons and $1g_{9/2}$ hole states for neutrons, are expected to be the main components of the nuclear wave functions in these nuclei. Proton subshell closures exist for Sr (Z=38, proton $1f_{5/2}$ shell) and Zr (Z=40, proton $2p_{1/2}$ shell). This allows for a systematic investigation of the evolution of collectivity in the vicinity of these subshell closures and the N=50 main shell. As shown in Fig. 1 detailed data exists for several heavier isotopes like, e.g., the N=52 isotones ^{92}Zr, ^{94}Mo, ^{96}Ru, and ^{98}Pd especially for the fundamental one-phonon quadrupole excitations (cf. [2]), the 2_1^+ state and another fundamental excitation of the ground state, the one-phonon proton-neutron mixed-symmetry 2^+ state. A decrease of collectivity was found in ^{92}Zr due to the aforementioned $2p_{1/2}$ subshell closure [2] where the lowest 2^+ states can be described mainly as two neutron (2_1^+) and two proton (2_2^+) excitations, respectively. However, the existing data shows that neither a purely collective picture nor restricted shell model calculations yield a fully satisfactory description of the observed structures [3].
For light exotic neutron-rich isotopes in the vicinity of doubly-magic ^{78}Ni data are more sparse. Especially the question whether the magic number N=50 survives for neutron-rich nuclei got in the focus of interest during the last years and experimental effort was done to clarify this question (see, e.g., [4, 5, 6]). Several experimental studies were done to probe this evolution of the N=50 shell far from stability. Those resulted in knowledge on excitation energies of even-Z N=49 and N=51 nuclei, particle-hole excitations of even-even nuclei across N=50 and $B(E2)$ values for ground state transitions of ^{78,80,82}Ge [7, 8] and ^{74,76,78,80}Zn [5] using post-accelerated radioactive ion beams. For an overview about the corresponding data sets in this region and experimental techniques see [4] and references therein. These data and newer results on two-neutron separation energies S_{2n} across N=50 [6] and conclusions from high precision mass measurements on neutron-rich Zn, Ga, Ge, As, and Se isotopes [4] prove a weakening of the N=50 shell gap towards Z=32 (Ge) and an increase in the region of Zn.
Therefore, our work aims to a further detailed investigation of this very interesting region by measuring absolute $E2$ transition strengths between yrast states in ^{86}Se determined from level lifetimes measured with the RDDS technique. The results will provide insight in the nuclear structure with respect to the strongly changing characteristics in this region. They will allow for a stringent test of the shell model with respect to the weakening of the shell gap in this region and in relation to the structure of the lowest states for heavier

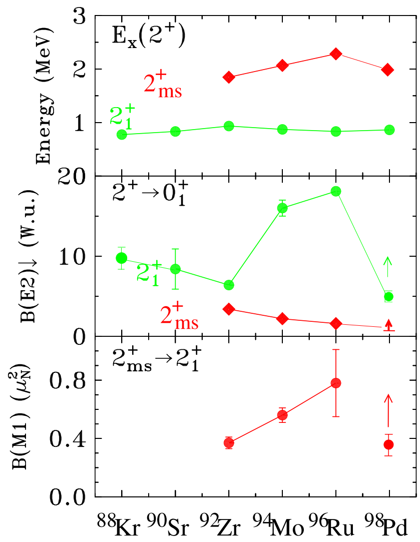

Figure 1: Systematics of the excitation energy and the $E2$ and $M1$ transition strengths of the fundamental quadrupole excitations in $N = 52$ isotones, the 2^+_1 and the 2^+ proton-neutron mixed-symmetry state.

N=52 isotopes (see, e.g., [2, 11, 12]). In addition, the validity of collective models can be tested to learn about the evolution of collectivity towards the light exotic N=52 isotones and doubly-magic ^{78}Ni.
A measurement on the neighboring radioactive N=52 isotope ^{88}Kr was already performed at REX-Isolde with Coulomb excitation in inverse kinematics [9, 10] resulting in a $B(E2, 2^+_1 \rightarrow 0^+_1) = 7.7(8)$ W.u. which is comparable to the $B(E2, 2^+_1 \rightarrow 0^+_1)$ values in neighboring ^{90}Sr and ^{92}Zr. This result does not give clear evidence for an increasing collectivity when leaving the proton subshell closure at Z=38.
^{86}Se was already investigated in a RDDS experiment performed by our group with the AGATA demonstrator in combination with the Cologne compact plunger and the magnetic spectrometer PRISMA at Legnaro using a four-neutron transfer reaction from ^{82}Se. In this experiment neighboring ^{84}Se was investigated via two-neutron transfer, too. Excited states in ^{84}Se were populated quite strongly allowing a precise determination of lifetimes of several low-lying states. However, the four-neutron transfer channel to ^{86}Se was very weak, thus these data will only allow for a rough measurement of the 2^+_1 lifetime. No lifetimes of higher states can be determined from the data which are analyzed at the moment. Therefore, a further experiment on ^{86}Se is required to yield precise data on level lifetimes of the lowest yrast states for a determination of $E2$ transition strengths.
The experiment further aims for the investigation along the Se isotopic chain, where an interesting development is proposed [13]. In the $N = 54$ isotope ^{88}Se the 2^+_1 state was found at 886 keV, higher in energy than in ^{86}Se ($E_{2^+_1}(^{86}\mathrm{Se}) = 704.1$ keV). As an explanation, an interaction of a low-lying 0^+ state with a different deformation and the ground band is expected for ^{88}Se [13]. The knowledge of absolute $E2$ strengths in ^{86}Se would help to establish an understanding of the characteristics of the Se isotopic chain. However, future measurements on even more exotic ^{88}Se would be desirable.

Table 1: Level and transition energies of yrast states in ^{86}Se. Doppler-shifted γ-ray energies from emission after target and degrader and the energy differences ΔE are given, too, for a forward angle of 45 degrees relative to the beam axis.

J^{Π}	E_{Level} [keV]	E_{γ}	$E_{\gamma,\mathrm{fast}}$ [keV]	$E_{\gamma,\mathrm{slow}}$ [keV]	ΔE [keV]
2_1^+	704.1	704.1	749.2	732.0	17.2
4_1^+	1567.9	863.8	919.1	898.0	21.1
6_1^+	2073.4	505.5	537.9	525.5	12.4

2 Experimental details

The RDDS measurement on ^{86}Se will be performed with Coulomb excitation in inverse kinematics. A radioactive ^{86}Se beam from HIE-ISOLDE with an energy of 4.6 MeV/u will be directed onto a 4.0 mg/cm^2 ^{197}Au plunger target and Coulomb excited. The beam energy is chosen to maximize the population of the higher spin states and to minimize other reaction channels, especially fusion evaporation (Coulomb threshold $\approx$ 400 MeV). Recoiling excited ^{86}Se nuclei will be degraded in a 8 mg/cm^2 ^{93}Nb degrader foil to a remaining energy of 1.44 MeV/u to allow for a recoil identification including the angle of the outgoing particle with the target CD detector. Depending on the distance between target and degrader foils and the lifetimes of the excited states in ^{86}Se specific fractions of γ-ray intensities will be emitted before (fast component) or after the degrader foil (slow component) from the emerging Coulomb excited ^{86}Se nuclei with certain recoil velocities allowing for a precise determination of the level lifetimes by measuring the ratios of these fractions. The two components are sufficiently separated for a RDDS analysis as shown in Table 1. Experimental details including the kinematics and target and degrader specifications are given in Table 2. It should be stressed that this experiment will be the first plunger measurement at MINIBALL. A big advantage of using Coulomb excitation as the population mechanism for the states of interest is that besides the analysis of lifetimes from the RDDS data an analysis of the Coulomb excitation data can be performed, too. This allows to check for the consistency of the results especially regarding multiple Coulomb excitation.

Table 1 lists the level and transition energies both unshifted and Doppler-shifted (both fast and slow components) for the yrast states in ^{86}Se. These data evindence that a good separation of the two components can be achieved with the chosen kinematics which allows the determination of lifetimes of these excited states.

It is intended to construct and build a new plunger apparatus for the MINIBALL spectrometer. The proposed measurement on ^{86}Se with the RDDS technique will be used to implement this device at HIE-ISOLDE also for future experimental campaigns with the RDDS method. Since the RDDS method is independent of the reaction mechanism it can be also used for other experimental probes like transfer reactions etc. A short description of the plunger device as it will be used in the experiment on ^{86}Se is given in the following. This device allows to precisely adjust the distance between target and degrader foil remotely controlled with an inchworm motor with a very high precision better than 1 μm. In addition, it is equipped with a feedback system that uses the capacitance between target and degrader foils to compensate for distance changes between the foils due to, e.g., ther-

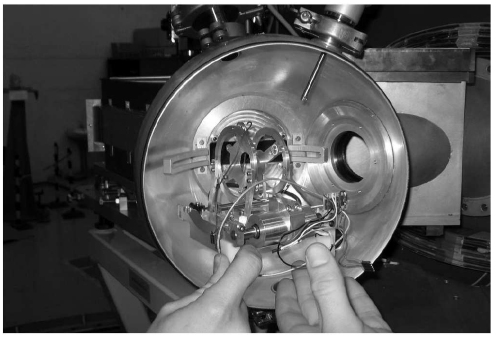

Figure 2: Cologne compact plunger used for RDDS experiments at the magnetic spectrographs PRISMA and VAMOS. The new plunger device for MINIBALL at HIE-ISOLDE will be based on this construction.

mal effects where the accuracy at small distances is better than $0.05\,\mu$m. This is crucial for these kind of lifetime measurements to determine nuclear level lifetimes with high precision (typically with errorbars smaller than 10%). In addition, the plunger is equipped with an optical distance measuring system "Tesatronic". Figure 2 shows a picture of the Cologne compact plunger device that was already used with great success in combination with the highly segmented AGATA demonstrator coupled to the PRISMA magnetic spectrograph at the Laboratori Nazionali die Legnaro (Italy) and with the EXOGAM γ-ray spectrometer coupled to the spectrograph VAMOS at GANIL (Caen, France). Our new plunger device will be based on this concept and especially designed for MINIBALL connected to the CD detector at this setup.
The plunger including electronics for the feedback system and the special target and degrader foils for the proposed experiment will be provided by our Cologne group.
In the following, we will outline the expected γ-ray yield. The ISOLDE beam list does not contain data for ^{86}Se. But for even more exotic ^{87}Se a SC yield of $5.6 \cdot 10^4$ ions/μC is given. Assuming a yield for ^{86}Se that is about a factor of 10 higher and a further slight increase by using the ISOLDE PSB and taking into account a transmission through the REX postaccelerator of about 3% a beam yield of $1 \cdot 10^5$ ^{86}Se ions per second at the MINIBALL target position seems feasible. Using this beam current and a Coulomb excitation cross section of 60 mbarn exemplarily estimated for the population of the 4_1^+ state in ^{86}Se with a beam energy of 4.6 MeV/u and assuming a photo peak efficiency of the MINIBALL array around 700 keV of 5% for detectors under forward and backward angles relative to the beam axis, we expect the observation of 12 γ rays per hour for the $4_1^+ \to 2_1^+$ γ-ray transitions of interest. Therefore, it would be necessary to measure 2 days per target-degrader distance to observe about 600 counts in the Doppler-shifted $4_1^+ \to 2_1^+$ γ-ray line which would allow a determination of the corresponding level lifetimes with the RDDS technique with an error of the order of 10%.
From a comparison to neighboring isotones we expect lifetimes of the lowest yrast states of the order of few picoseconds. Therefore, due to a recoil velocity after the target of about 27 μm/ps we propose to measure at four different target–degrader distances in the range from 10 μm up to 200 μm to get the lifetimes of interest with sufficient precision.

Table 2: Experimental details of the experiment on ^{86}Se with Coulomb excitation in inverse kinematics.

Energy [MeV]	4.6 MeV/u
Intensity [pps]	$1 \cdot 10^5$
Target	^{197}Au
Thickness of Target [mg/cm^2]	4.0
Outgoing velocity β after target [c]	9.0%
Degrader Foil	Nb (nat.)
Thickness of Degrader [mg/cm^2]	8
Outgoing velocity β_2 after degrader [c]	5.6%

Therefore, 24 shifts are required to complete the measurement on ^{86}Se. In addition, three shifts would be needed to perform a measurement to determine a contribution to the γ-ray intensities from Coulomb excitation on the Nb degrader. Further, beam development time is required to get a ^{86}Se beam with the intensity necessary for this experiment, especially regarding a likely beam contamination from the isobar ^{86}Rb.

3 Summary

An experiment is proposed to measure lifetimes of yrast states in ^{86}Se with Coulomb excitation in inverse kinematics using the RDDS technique and a new Cologne plunger device for the first time at MINIBALL. The aim is to learn about the evolution of nuclear structure and appearance of collectivity in neutron-rich exotic nuclei in the A=80 region and a weakening of the N=50 shell gap from a measurement of absolute $E2$ transition strengths. In addition, this experiment will serve to implement the RDDS technique and a new plunger device at HIE-ISOLDE combined with MINIBALL.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
MINIBALL + CD	☒ Existing	☒ To be used with modifications: Plunger including target chamber needs to be added
Proposed experiment on ^{86}Se	☒ New	New plunger device will be supplied by Cologne group including electronics (feedback system for plunger) Modified or new target chamber will be supplied, too