New developments on the Recoil Distance Doppler-Shift Method

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Abstract. Absolute transition probabilities are fundamental observables for nuclear structure. The recoil-distance-Doppler-shift (RDDS) technique, also called plunger technique, is a well established tool for the determination of these important experimental quantities via the measurement of lifetimes of excited nuclear states. Nowadays nuclear structure investigations are concentrated on exotic nuclei which are often produced with extremely small cross sections or with very low beam intensities. In order to use the RDDS technique also for the investigation of very exotic nuclei this method has to be adapted to the specific needs of these special reactions. This article gives an overview on recent RDDS measurements with the new differential plunger in combination with particle detectors and recoil spectrometers. These were done with projectile multistep Coulomb excitation at low beam energies ($\approx 5\text{ MeV/u}$) and at intermediate beam energies ($\approx 100\text{ MeV/u}$) using one step Coulomb excitations and knockout reactions.

1. Introduction

Present day nuclear structure physics focuses on the investigation of exotic nuclei far away from the valley of stability. Absolute transition strengths of excited states of these nuclei provide crucial information on the nuclear structure. This allows to extend the knowledge on the evolution of nuclear properties to extremely proton or neutron rich nuclei and gives the opportunity to test nuclear models in these regions. Absolute transition strengths can be determined from lifetimes of excited nuclear states. However, the measurement of lifetimes
in exotic nuclei is very challenging because such nuclei can often be produced only with low production rates due to extremely low cross sections or beam intensities.

The recoil distance Doppler-shift method (RDDS) is a very valuable method for the determination of lifetimes of excited nuclear states and it was discussed in detail, e.g., in [1]. The advantage of this method is that it does not depend on the excitation mechanism. In this article we will describe the adoption of the RDDS method to the measurement of lifetimes of excited nuclear states of very exotic nuclei. These nuclei are typically investigated in experiments with inverse kinematics because the beam production is done, e.g., with in-flight fragmentation and the identification of the exotic beams before and after the secondary target, where the nuclei of interest are excited, is required. Different reactions like fusion, Coulomb excitation, or knockout reactions can be used. In section 2 we will briefly describe the experimental method. In section 3 a lifetime measurement on the stable nucleus $^{128}$Xe with multistep Coulomb excitation in inverse kinematics is discussed. This served mainly as a test of the novel experimental method which is expected to be efficiently used in future radioactive beam experiments at energies of about 5–10 MeV/u. The following section 4 gives an overview on the measurements performed in the recent past on radioactive nuclei with the Cologne differential plunger at the National Superconducting Coupled Cyclotron Laboratory (NSCL) at Michigan State University, where both Coulomb excitation and knockout secondary reactions were used.

2. The Cologne differential plunger

The recoil distance Doppler-shift method (RDDS) is a standard method to measure lifetimes of excited nuclear states in the picosecond range. The beam hits a thin target foil and after the nuclear reaction the recoils leave the target foil with the average speed $v$. Excited states in these nuclei decay via $\gamma$ decay both after the recoil is stopped in a stopper foil with an unshifted $\gamma$ ray with energy $E_u$ and in flight whereas (for the non-relativistic case) a Doppler-shifted $\gamma$ ray with energy

$$E_s = E_u \cdot (1 + \frac{v}{c} \cdot \cos \theta)$$

is observed in a detector positioned under an angle $\theta$ relative to the beam axis (see Fig. 1).

![Figure 1. Principle of the RDDS method. $E_s$ and $E_u$ are the Doppler-shifted and unshifted $\gamma$-ray energies, respectively, observed with a high-purity Germanium detector.](image)

From the intensities $I_s$ and $I_u$ of shifted and unshifted components for different target to stopper distances and known reaction kinematics one can deduce the lifetime of an excited state independent of the reaction mechanism via the differential decay curve method (DDCM) [2, 3]. Typically, an excited state is populated both from the continuum after a nuclear reaction and also from discrete higher lying states with finite lifetimes. Thus the decay curve of the state of interest involves the population and depopulation history of all states that decay directly or
indirectly to this state. The fundamental differential equation follows from the radioactive decay law \( \dot{n}_i(t) = -\frac{1}{\tau_i}n_i(t) = -\lambda_in_i(t) \) and the superposition of all involved states

\[
\dot{n}_i(t) = -\lambda_in_i(t) + \sum_h b_{hi}\lambda_hn_h(t),
\]

(2)

where \( n_h(t) \) is the number of nuclei in a feeding level \( l_h \) at time \( t \) and \( b_{hi} \) is the decay branching ratio of the transition from level \( l_h \) to \( l_i \).

After integration and transformation of this equation one can deduce the fundamental equation of the DDCM for lifetime determination, where \( N_h, N_i \) are the numbers of nuclei that decayed after a time \( t \) from level \( h,i \), respectively

\[
\tau_i(t) = \frac{N_i(t) - \sum_h b_{hi}N_h(t)}{\frac{d}{dt}N_i(t)}.
\]

(3)

\( N_i \) and \( N_h \) are proportional to the flight and stop peak intensities. One gets an independent value \( \tau_i(t) \) for the lifetime of the level of interest for every target to stopper distance \( d_i \), whereas \( t_i = d_i/v \). If the values for \( \tau_i(t) \) are plotted as a function of the distance \( d_i \) a constant value is expected. A deviation from this is an indicator for a systematical effect that has to be taken into account, like, e.g., unobserved sidefeeding from higher lying levels or deorientation. The latter results from hyperfine interaction of the spins of the recoils with the electron shell during the flight and causes a change of the nuclear orientation with time and thus a change of the angular distribution of the emitted \( \gamma \) rays. This effect is discussed in section 3. The analysis of \( \gamma\gamma \) coincidences can circumvent this problem as is pointed out in [4], but due to the aforementioned low production cross sections for radioactive ion beams resulting in low statistics of the measured \( \gamma \) rays usually only singles spectra can be obtained.

For measurements with radioactive ion beams typically recoil identification is necessary because the reaction produces a cocktail beam. In that case often a mass or fragment separator is used to identify the recoils in coincidence with the emitted \( \gamma \) rays. Therefore, the stopper foil of the “standard” plunger has to be replaced by a degrader foil that slows down the recoils rather than stopping them. The degrader foil has to be chosen in a way that a clear separation of the two Doppler-shifted \( \gamma \)-ray lines, one emitted between target and degrader (“flight peak”) and one emitted after the degrader (“degraded peak”), becomes possible.

Figure 2. Example of a measurement with the differential plunger. The stopper is replaced by a degrader to allow an identification of the recoils. Given are the energies of a \(^{114}\text{Pd}\) beam before and after the target and after the degrader and the correspondig velocities.

\[
E\sim70 \text{ MeV/}\mu\text{u} \quad E^{'}\sim60 \text{ MeV/}\mu\text{u} \quad E^{\prime\prime}\sim44 \text{ MeV/}\mu\text{u}
\]

Figure 2 depicts the principle of the differential plunger. As an example, the data of a measurement with Coulomb excitation in inverse kinematics on \(^{114}\text{Pd}\) at NSCL with the S800 mass separator to identify the \(^{114}\text{Pd}\) recoils in a cocktail beam [5] is included.
Figure 3. Photograph of the new Cologne differential plunger.

Figure 3 shows a photograph of the new Cologne differential plunger as it was used for the experiments with radioactive ion beams at the NSCL. There are several modifications as compared to the “standard” Cologne plunger for stable beams. Target and degrader foils with diameters up to 4 cm can be used. The foils can be moved to a maximum distance of 2.5 cm with a precision of 1 µm. This large separation is necessary to perform measurements at intermediate beam energies. In the following sections we will give an overview on the recent experiments with the differential plunger.

3. Experiment on $^{128}$Xe

An experiment on the stable nucleus $^{128}$Xe was performed at the University of Jyväskylä, Finland, with the Cologne plunger and the JUROGAM Germanium detector array. The measurement was done using Coulomb excitation in inverse kinematics. The main aim was the proof of the method of combining the RDDS technique with projectile multistep Coulomb excitation because such measurements are of high interest for future radioactive beam experiments. Further, $E2$ transition strengths in $^{128}$Xe were to be measured since this nucleus has been a considered candidate for an E(5) nucleus, i.e., a nucleus at the critical point of the shape phase transition from a spherical vibrator to a $\gamma$-soft nucleus [6].

![Sketch of the setup](image)

Figure 4. Sketch of the setup of the Coulomb excitation experiment on $^{128}$Xe with the differential plunger.

A sketch of the setup is given in Fig. 4. The $^{128}$Xe nuclei with an energy of $E(^{128}$Xe) = 525 MeV are Coulomb excited on an Fe target foil and Fe nuclei are knocked out of the target. As a degrader, a 4 mg/cm$^2$ Nb foil was used. However, $^{128}$Xe nuclei are also Coulomb excited
on the degrader foil. To separate projectile Coulomb excitation on target and degrader the γ rays from $^{128}\text{Xe}$ are observed in coincidence with Fe target recoils detected with photo diodes mounted behind a gold beam stopper foil that also stops the Nb degrader recoils. Furthermore, the photo diodes are arranged such to allow a separation of different recoil angles to improve the energy resolution of the emitted γ rays. Otherwise, the large angle spread of the $^{128}\text{Xe}$ nuclei after Coulomb excitation would prevent a clear separation of flight and degraded components of the γ-ray lines of interest.

As mentioned before, deorientation is an effect that has to be taken into account when analyzing a RDDS measurement in γ-ray singles spectra. The hyperfine interaction causes the original nuclear spin alignment to diminish in flight as a function of the interaction time. Figure 5 shows the intensities of flight and degraded component of the $4_1^+ \rightarrow 2_1^+$ transition in $^{128}\text{Xe}$. Obviously the sum of these intensities is not constant for different distances due to deorientation (most upper curve). Thus a correction had to be performed for the γ-ray intensities at different distances between target and degrader. The upper curves for both the flight and degraded component give the corrected intensities used for the lifetime determination. Details on these corrections are given in [7].

Our experiment yielded a total of six lifetimes of excited nuclear states and eleven $E2$ transition strengths of the lowest collective excitations in $^{128}\text{Xe}$. Lifetimes of the yrast states up to the $6_1^+$ state and of the $2_2^+$, $4_2^+$, and $3_1^+$ states were determined. The data for the yrast states are in quite good agreement with the literature values for these states [8]. More details on this experiment and the interpretation of the results can be found in [7] and will be published in a forthcoming article.

4. Experiments on radioactive isotopes
In this section we give an overview about recent lifetime measurements on radioactive isotopes with the new Cologne differential plunger at NSCL. The experiments used the combination of the NSCL Coupled Cyclotron Facility for the acceleration of the primary beams, the A1900 mass...
4.1. Knockout reactions
The aim of this experiment, described in detail in [13], was the measurement of lifetimes of the lowest excited states in $^{64}$Ge and $^{62}$Zn in single neutron knockout reactions. A cocktail beam of 5% $^{65}$Ge, 35% $^{64}$Ga, 52% $^{63}$Zn, and 8% $^{63}$Cu was produced via in-flight fragmentation of $^{78}$Kr at 150 MeV/u [14]. A 500 μm thick $^{12}$C target and a 250 μm thick $^{93}$Nb degrader were used. This resulted in velocities of the reaction products of $\beta_{\text{tar}} \approx 0.39$ after the target and $\beta_{\text{deg}} \approx 0.35$ after the degrader. The Doppler-shifted γ rays were observed with the SeGA array with two rings at laboratory angles of 30° and 140° and at three target to degrader distances of 0, 200, and 500 μm. Fig. 6 shows the Doppler-shifted $2^+_1 \rightarrow 0^+_1$ decay transition in $^{62}$Zn for illustration. The lineshapes also included in Fig. 6 were calculated from the velocities after target and degrader, considering relativistic effects, and only lifetime and normalization factor were taken as free parameters.

Figure 6. Doppler-shifted $2^+_1 \rightarrow 0^+_1$ transition in $^{62}$Zn for three target to degrader distances.

For $^{62}$Zn a lifetimes of the $2^+_1$ state of $\tau = 4.2(7)$ ps was measured in perfect agreement with a value from the literature of 4.2(3) ps [15]. For the $N = Z$ nucleus $^{64}$Ge the results for the first measurements of the lifetimes of the $2^+_1$ and $2^+_2$ states are $3.3(5)$ and $8^{+4}_{-2}$ ps, respectively [13]. A comparison of these results with GXPF1A shell model calculations can be also found in [13].

4.2. Investigation of heavy Palladium isotopes with Coulomb excitation
Absolute transition strenghts of the $2^+_1$ states in $^{110,114}$Pd were measured with the setup described in the previous section with the RDDS technique following Coulomb excitation at intermediate energies [5]. The $^{110}$Pd data were used to check the data analysis and this novel experimental technique. The motivation of the measurement of $^{114}$Pd is the fact that the known...
Figure 7. $E2$ excitation strengths to the $2^+_1$ states in Pd isotopes including the new value for $^{114}\text{Pd}$ from [5]. The data is compared to that of the neighboring Ru and Cd isotopic chains and to a prediction with the Grodzins rule.

$B(E2, 2^+_1 \rightarrow 0^+_1)$ value [16] strongly deviated from predictions of the Interacting Boson Model [17] or from the Grodzins relation [18].

The intensities of the $^{110}\text{Pd}$ and $^{114}\text{Pd}$ beams were 11 000 pps and 1500 pps, respectively. They impinged on a 100 $\mu$m $^{93}\text{Nb}$ target and a 500 $\mu$m thick carbon degrader. The velocities and energies before and after the target and after the degrader are given in Fig. 2. The experiment yielded lifetimes of the $2^+_1$ states in $^{110}\text{Pd}$ and $^{114}\text{Pd}$ of $\tau = 67(8)$ ps and $\tau = 118(20)$ ps, respectively. The value for $^{110}\text{Pd}$ is in a good agreement with the average literature value which gives us confidence in the method. The value for $^{114}\text{Pd}$ is more than two times smaller than the previous result [16]. The resulting $E2$ strengths are plotted in Fig. 7 in comparison to the prediction of the Grodzins relation and to the neighboring isotopes. The new $B(E2)$ value for $^{114}\text{Pd}$ fits nicely in the systematic trend deduced for the lighter isotopes.

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