Lifetime determination via the particle-γ coincidence 
Doppler-shift attenuation method

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Abstract. This paper illustrates the principle of the Doppler-shift attenuation method (DSAM) using particle-γ coincidences, a method for determining lifetimes of excited nuclear levels in the range of few femtoseconds up to one picosecond. The coincident detection holds several advantages towards conventional DSAM experiments, such as the elimination of background and feeding transitions. Using the experimental data on 94Zr, the concept of the (p,p'γ) DSAM analysis is presented. Additional experimental results are highlighted.

1. Introduction
Nuclear level lifetimes are important observables to probe the properties of atomic nuclei. Transition probabilities can be extracted and the accuracy of model calculations can be tested. Since lifetimes of different excited states can span several orders of magnitude, different experimental methods have to be used for accessing specific lifetime ranges [1]. The (p,p'γ) Doppler-shift attenuation method (DSAM) presented here targets very short lifetimes, ranging from few femtoseconds up to the low picosecond regime.

An overview of the method is given in section 2, including a description of the advantages of using particle-γ coincidences. In section 3, the experimental setup for this method is presented, and the analysis is described in section 4 based on the example of the nucleus 94Zr. Results of this experiment as well as an overview of previous experiments are given in section 5.

2. Particle-γ coincidence Doppler-shift attenuation method
DSAM is based on the detection of Doppler-shifted γ-rays from the de-excitation of a moving target nucleus. As opposed to the recoil distance Doppler-shift (RDDS) method [2], the target nucleus is slowed down continuously while recoiling through the target and subsequent stopper material after its excitation by inelastic scattering. Knowing the initial velocity of the recoil, its slowing-down process can be simulated, yielding a velocity distribution throughout the stopping process. Since the Doppler shift of the emitted γ-rays directly depends on the velocity of the recoiling target nucleus at the time of de-excitation, this velocity distribution can be used to determine the time after excitation at which the de-excitation took place, namely the lifetime τ of the level of interest. As illustrated in Fig. 1, a de-excitation with a short lifetime happens
Figure 1. Schematic drawing of an excited target nucleus de-exciting via a γ-ray with a Doppler-shifted energy at different times $t_i$ while being slowed down continuously in the target backing (grey) to a respective velocity $v_i$. Shorter lifetimes correspond to earlier decays.

Figure 2. Schematic plot of the inelastic proton scattering used for the DSAM measurement. A charged-particle detector for the scattered proton $p'$ and a HPGe detector for the Doppler-shifted γ-ray energy $E_\gamma(\Theta)$ are indicated.

shortly after the excitation, leaving the recoil nucleus little time to be slowed down, therefore resulting in a large Doppler shift of the detected γ-ray energy. Due to the continuous stopping a level with a longer lifetime will result in a slower recoil at the time of decay, showing a weaker Doppler shift. Thus, lifetimes in the order of the time it takes to stop the recoil can be determined with this method. In experiments performed with the setup presented in section 3, the stopping time amounts to approximately a few picoseconds [3]. The connection between the velocity and the lifetime is contained in the attenuation factor $F(\tau)$.

The connection between the velocity and the lifetime is contained in the attenuation factor $F(\tau)$. It is connected to the shifted centroid energy $E_\gamma(\Theta)$ of the de-exciting γ-ray via

$$E_\gamma(\Theta) = E_{\gamma,0}(1 + \frac{v_0}{c} \cdot F(\tau) \cdot \cos \Theta),$$

where $E_{\gamma,0}$ is the unshifted decay energy, $\Theta$ the angle between the direction of motion of the recoil and the emitted photon, and $v_0$ is the initial recoil velocity in units of $c$. All of these parameters can be extracted from the data and used to determine the lifetime $\tau$ by a comparison to a Monte-Carlo simulation of the stopping process [1, 3, 4].

2.1. Advantages of particle-γ coincidence detection

In contrast to conventional DSAM approaches, the scattered charged particle used for the excitation of the target nucleus in the method presented here is detected in coincidence with the emitted γ-ray. This leads to several advantages for the determination of lifetimes [3, 5, 6]. Firstly, the reaction kinematics can be derived from the energies and the detection positions of the scattered particle and emitted γ-ray. Therefore, the direction of motion of the recoil is known, which allows to reconstruct its trajectory relative to the emitted γ quantum. As seen in Eq. (1), a larger overlap of the trajectories, given by the factor $\cos \Theta$, amounts to a larger Doppler shift in the γ-ray’s energy. Furthermore, the excitation energy can be derived from the energy of the scattered particle. This allows the selection of only γ-rays coincident with the de-excitation of a level of interest, known as gating. Its benefits are illustrated in Fig. 3. Thus, feeding from the decay of higher-energetic states which would extend the measured lifetime can be eliminated. Using charged particles for the excitation in the DSAM measurement furthermore requires about $10^5$ times less target material compared to DSAM-INS experiments [7], giving the possibility to study less abundant isotopes.
3. Experimental setup
The particle beams for the inelastic scattering experiments are provided by the 10 MV FN tandem accelerator of the Institute for Nuclear Physics of the University of Cologne. Coincidence data are taken with the SONIC@HORUS setup [8], consisting of the HORUS γ-ray detector array equipped with 14 HPGe detectors for the detection of the emitted photons, positioned under the angles 35°, 45°, 90°, 135° and 145° with respect to the beam axis. Six of these detectors can be combined with BGO shields for active Compton background suppression. Mounted into HORUS is the SONIC charged particle identification chamber, serving as a target chamber as well as an array for the detection of the scattered particles. It also includes a 56Co calibration source on the target ladder. Several versions of this chamber have been used since 2013, employing 6 to 12 PIP silicon detectors which results in up to 168 combinations of particle and γ-ray detectors. In the current version, SONIC v3, four rings of four silicon detectors each are installed at the angles \( \theta = 107°, 123°, 145° \) with respect to the beam axis in a plastic frame. The setup is explained in greater detail in [8].

For presenting the DSAM analysis in this paper, the \(^{94}\)Zr(\(p,p′\)γ) reaction is used as an example. Here, a beam energy of 8.05 MeV and a target of 0.5 mg/cm\(^2\) \(^{94}\)Zr on a 1.0 mg/cm\(^2\) \(^{197}\)Au stopper backing were used.

4. Data analysis
4.1. Reaction kinematics
The coincidence data obtained with SONIC@HORUS, with a trigger on the charged particles, are processed into \(pγ\)-coincidence matrices, as shown in Fig. 4 for \(^{94}\)Zr. Clearly, the ground-state decay diagonal at equal excitation and decay energy as well as diagonals corresponding to decays into excited states towards higher excitation energies are visible. For this, the excitation energy \(E_x\) of the recoil nucleus is calculated from the (position and) energy of the scattered particle \(E_p′\), roughly following

\[
E_x \approx E_{\text{beam}} - E_{p′} - E_{\text{loss}}
\]

where \(E_{\text{beam}}\) is the beam energy and \(E_{\text{loss}}\) the energy loss of the scattered particle in the target and stopper [3]. The angle between the recoil nucleus and the emitted γ-ray, \(\Theta\), is also calculated.
4.2 Experimental attenuation factor

The lifetime information is contained in the attenuation factor $F(\tau)$ which can be obtained experimentally by a linear fit of the shifted energy centroids as a function of $\cos \Theta$ (see Eq. (1)) [1, 3]. For that, the coincident events from all particle-\(\gamma\) detector combinations are sorted according to their respective values of $\cos \Theta$ for a given excitation energy into equally binned angular groups. Depending on the statistics of the experiment, the number of angular groups a data set is split into varies. For $^{94}\text{Zr}$, eleven groups were employed, maximizing the number of groups from which centroid shifts can be extracted to optimise the angular resolution while still maintaining sufficient statistics in each angular group. For transitions with lower statistics, a splitting into fewer groups is necessary. In the resulting particle-\(\gamma\) coincidence matrices of each group an excitation-energy gate on the level of interest is applied and the energy centroid of the decay transition is determined. An example showing the decay of the $1^{+}$ state at 3.2 MeV for three groups is given in the left part of Fig. 5. In black, the unshifted transition peak at $\Theta = 90(5)^{\circ}$ is shown. A shift towards higher energies is given in blue for the group corresponding to the forward angle $\Theta = 34(6)^{\circ}$. Backward angles, here represented by $\Theta = 146(6)^{\circ}$ in red, result in a shift towards lower centroid energies. A linear fit to the centroids from all angular groups, as shown in the right part of Fig. 5, then yields the experimental attenuation factor $F_{\text{exp}}(\tau)$, calculated from the slope $a$, the unshifted photon energy $E_{\gamma}^{0}$ and the initial recoil velocity $v_{0}$ in units of $c$ via

$$F_{\text{exp}}(\tau) = \frac{a}{E_{\gamma}^{0} \cdot \frac{v_{0}}{c}}.$$
4.3. Monte-Carlo simulation of the stopping process

For the comparison of the experimental and theoretical attenuation factor, the stopping process of the recoil is simulated in a Monte-Carlo simulation according to the stopping theory of Lindhard, Scharff and Schiøtt (LSS theory) [9]:

$$\frac{d\varepsilon}{d\rho} = \left(\frac{d\varepsilon}{d\rho}\right)_e + f_n \left(\frac{d\varepsilon}{d\rho}\right)_n$$

(6)

taking into account continuous stopping in the fields of the electrons of the surrounding materials \((e)\) as well as discrete energy losses by collisions with atomic nuclei \((n)\). Whereas the correction factor \(f_n\) is empirically set to 0.7, the parameters \(f_e\), \(k_{LSS}\) and \(a\) for the electronic stopping power

$$\left(\frac{d\varepsilon}{d\rho}\right)_e = f_e \cdot k_{LSS} \cdot \varepsilon^a$$

(7)

are obtained by a fit to the semi-empirical stopping power tables of Northcliffe and Schilling [10]. A correction for the atomic structure of the stopping medium as presented by Ziegler and Biersack [11] is added. The Monte-Carlo code DSTOP96_PPPRIME_2 [12], following the DESASTOP code introduced by Winter [13], uses these parameters as input to obtain a theoretical attenuation factor \(F_{theo}(\tau)\) for any possible lifetime throughout the stopping process as plotted in Fig. 6. The lifetime is then determined by a comparison of the experimentally obtained attenuation factor to the theoretical curve. An electronic stopping-power uncertainty of 10% is taken into account (dotted lines) in the systematic uncertainty of the lifetime.
5. Results and conclusion
In the analysis of the $^{94}$Zr(p,p'γ) experiment, 13 lifetimes and one upper limit were determined which are in excellent agreement with results from a DSAM-INS experiment [14], as shown in Fig. 7. A comparison of additional results obtained with the particle-γ coincidence DSA technique in Cologne to other methods, such as Coulex and ($γ$, γ') on the example of $^{96}$Ru [3] as well as RDDS and other DSAM approaches on $^{112,114}$Sn [15] confirms the reliability of the presented method. Dozens of lifetimes of low-spin states can be determined in a single experiment, which was successfully shown, amongst others, in the experiment on $^{112,114}$Sn [15]. Lifetimes obtained with this method are used, e.g., for the study of collective excitations such as mixed-symmetry states [16]. Similar experiments to study nuclear structure via lifetime measurements using the particle-γ coincidence DSA technique are currently performed and evaluated. In summary, DSAM using particle-γ coincidences is a powerful tool to determine lifetimes of excited nuclear levels in the fs to ps regime without feeding contributions.

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