Investigation of exotic nuclei with absolute transition probabilities

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Abstract. Transition probabilities are crucial for the understanding of nuclear structure. Deep inelastic reactions, knockout reactions and projectile Coulomb excitation with fast radioactive beams are suited to populate excited states in exotic nuclei. Examples are presented which demonstrate that recoil Doppler shift lifetime measurements can be applied successfully in combination with such reactions to measure level lifetimes.

1. Introduction
In order to investigate exotic nuclei far from the line of stability deep inelastic reactions or reactions with radioactive beams have been used successfully. Absolute transition probabilities which are crucial for the understanding of nuclear structure can be deduced directly from lifetimes of excited states measured with the recoil distance Doppler shift (RDDS) method or plunger technique. Therefore it is of great interest to apply the plunger technique in combination with such reactions and with fast radioactive beams. In this paper examples are presented which prove that the RDDS technique in combination with the above mentioned reactions can be very useful. For radioactive ion beam experiments only beam energies around 100 MeV/u are considered here. A general description of the plunger technique and recent developments can be found in [1].

With fast radioactive beams both Coulomb excitation and knockout reactions have been used. Since the beam intensities which can be provided nowadays for experiments are still limited, it is often necessary to get some compensation by using thick targets (up to 1000 µm). At beam energies of about 100 MeV/u only one step Coulomb excitation occurs. That means that in such experiments only lower 2+ states of even-even nuclei can be excited. This is a considerable limitation of the method but, on the other hand, it also means that the problem with unknown level feeding is practically eliminated.

2. RDDS after fast projectile Coulomb excitation
As an example of a RDDS lifetime measurement after fast projectile Coulomb excitation I want to present the measurement aiming for the lifetime of the 21+ states in the neutron rich 62,64,66Fe nuclei [2]. This experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University (NSCL/MSU) where the secondary Fe beams were produced by fragmentation of a primary 76Ge beam at 130 AMeV. The generated fragments were purified by the A1900 [3] fragment separator. Rather pure Fe beams were delivered and directed to the secondary target (300 µm thick Au) which was mounted in a dedicated plunger device [4], built at the Institute for Nuclear Physics of the University of Cologne (see Fig. 1) and mounted at the target position of the S800 spectrometer [5]. Instead of the standard stopper foil a degrader foil was used (400 µm thick Nb) which enables a detection of the recoiling nuclei produced in the secondary reaction. The plunger
device allows to set different target-degrader-separations. The S800 spectrometer was used to identify Coulomb excited Fe nuclei. The gamma spectra were measured with the SeGA array [6]. Spectra which have been measured at different target-degrader distances and with SeGA detectors positioned at different angles with respect to the beam axis are shown in Figure 2 after Doppler correction. The lifetimes were determined from a simulation which aims to reproduce the two components of the gamma transition of interest simultaneously in all spectra using the level lifetime as a free parameter. The resulting simulated spectra are shown as solid curve in Figure 2. The obtained results can be found in Table 1 of [2].

![Simulated spectra of gamma transitions in Fe](image)

**Fig1:** Results from gamma-ray line-shape fits (blue line) to Doppler corrected spectra for the $2_1^+ \rightarrow 0_1^+$ transitions in $^{62,64,66}$Fe

### 3. RDDS after knockout reactions using fast radioactive beams

Via knockout reaction higher lying levels with medium spins can be populated. This fact increases considerably the potential of the RDDS technique with fast radioactive beams. The first pioneering plunger experiment with fast radioactive beams using knockout reactions as secondary reactions was on $^{62}$Zn and $^{64}$Ge [7]. Unfortunately the level feeding cannot be neglected as in the case of one step Coulomb excitation and has to be considered in the data analysis. However, in contrast to standard compound fusion reactions it has been found that only transitions which have been observed in the experiment have to be considered [7]. Thus the level feeding is less complex than that of a standard compound fusion reaction where many long cascades feed the lower levels which are observed in the experiment. In a knockout reaction the feeding times are very close to the level lifetimes from which the feeding occurs since only one or two step feeding can be assumed. This makes the consideration of the feeding after knockout reactions much easier as compared to the compound fusion reaction. A recent experiment was performed at the NSCL/MSU aiming to measure lifetimes in neutron rich Cr isotopes. A primary $^{82}$Se beam of 140 AMeV was fragmented at a beryllium production target. The secondary beams of $^{59,61,63}$Mn were purified with the A1900 fragment separator and directed on beryllium plunger targets (288µm/$^{58}$Cr, 520µm/$^{60}$Cr, 1295µm/$^{62}$Cr). These targets with different thickness were used to compensate partially the different $^{59,61,63}$Mn beam intensities.

In Fig. 3 examples of Doppler corrected $\gamma$-ray spectra of $^{58}$Cr are shown. The intensities of the feeding transitions which are considered in the final data analysis were deduced from so called “target only” spectra which are generally of higher quality that the ones where a degrader foil has been used. The actual lifetime analysis was performed in two ways: via simulation of the spectra aiming to reproduce the fast and degraded components simultaneously in all spectra corresponding to different target-degrader separations and by using the extracted decay curves.
Table 1: Measured transition strengths of $^{58,60,62}\text{Cr}$ (preliminary) compared with LNPS calculations [8]. The B(E2;6$^+\rightarrow4^+$) values were determined from effective lifetimes only. Therefore these values have to be considered as lower limits only.

| A    | $J_{\sigma_2} \rightarrow J_{\sigma_1}$ (preliminary) | LNPS $\text{B(E2)}$ [e²fm] |
|------|-----------------------------------------------------|----------------------------|
| $^{58}\text{Cr}$ | $2_1^+ \rightarrow 0_1^+$ | 206$^{32}_{24}$ |
|     | $4_1^+ \rightarrow 2_1^+$ | 206$^{41}_{28}$ |
|     | $6_1^+ \rightarrow 4_1^+$ | $\geq 183^{55}_{34}$ |
| $^{60}\text{Cr}$ | $2_1^+ \rightarrow 0_1^+$ | 285$^{37}_{30}$ |
|     | $4_1^+ \rightarrow 2_1^+$ | 345$^{55}_{43}$ |
|     | $6_1^+ \rightarrow 4_1^+$ | $\geq 173^{53}_{33}$ |
| $^{62}\text{Cr}$ | $2_1^+ \rightarrow 0_1^+$ | 357$^{65}_{47}$ |
|     | $4_1^+ \rightarrow 2_1^+$ | 531$^{72}_{47}$ |

Preliminary transition probabilities are consistent to previously measured B(E2;2$^+\rightarrow0_1^+$ values) [9]. The experimental transition probabilities are presented in table 1 together with shell model calculations [8].

**RDDS after deep inelastic reactions**

An alternative way to produce exotic nuclei is offered by deep inelastic reactions. Since the cross sections are normally very low it is needed to clean the measured gamma spectra by demanding a coincidence with detected recoil nuclei in the focal plane of magnetic spectrometer like e.g. PRISMA [10] at the LN Legnaro/Italy or VAMOS [11] at GANIL/France. The reaction cross sections are strongly dependent on the emission angles of the nuclei produced in the reaction with respect to the beam axis. Therefore a special plunger device is needed which allows the recoils after leaving the target to pass the degrader foil at angles up to 70° and to enter into a spectrometer to detect and identify them. Such a plunger device was built at the Institute of Nuclear Physics of the University of Cologne and is

![Figure 4: Plunger positioned in the target chamber in front of the PRISMA spectrometer](image-url)
shown in Figure 4. Pioneering experiments were done at Legnaro [12,13] using the PRISMA spectrometer and the CLARA HP-Ge-detector array [14] for the gamma detection.

Recently the CLARA array was replaced by the gamma tracking spectrometer AGATA in its first implementations (AGATA-Demonstrator) [15,16]. With this setup a first plunger experiment was performed for $^{70,72,74}$Zn [17]. Our group performed with this setup a lifetime measurement on $^{84,86}$Se in collaboration with groups from IPNO/CNRS-University Paris Sud-11, IPHC/CNRS-University of Strasbourg and the INFN LN Legnaro and others participating in the experiment No. 10.41.

We used a $^{82}$Se beam at 557 MeV which was impinging on the target at an angle of 15° with respect to the normal on the plane defined by the stretched target. The recoils were registered with the PRISMA spectrometer at an angle of 58° with respect to the beam axis. The target consisted of 2 mg/cm² $^{238}$U evaporated on 1.2 mg/cm² thick Ta backing. As a degrader a $^{93}$Nb foil with a thickness of 4 mg/cm² was used which was sufficient to reduce the recoil velocity such that two separated Doppler shifted components of the transitions of interest were obtained in the gamma spectra (see Figure 5).

The analysis of the data is still ongoing.

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