Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Analysis of Nuclear Lifetimes Using the Gamma-ray Induced Doppler Shift Attenuation Method

To cite this article: F.C.L. Crespi 2018 *J. Phys.: Conf. Ser.* **1023** 012005

IOP Conf. Series: Journal of Physics: Conf. Series **1023** (2018) 012005 doi:10.1088/1742-6596/1023/1/012005

Analysis of Nuclear Lifetimes Using the Gamma-ray Induced Doppler Shift Attenuation Method

F.C.L. Crespi

Università degli Studi di Milano and INFN, Milano, I-20133, Italy

fabio.crespi@mi.infn.it

Abstract. Lifetime measurements allow extraction of fundamental information on the nature of the excited states of a nuclear system. Since nuclear lifetimes cover many orders of magnitude, a number of experimental techniques and detection setups have been developed depending on the range of the lifetime of interest. The Gamma-ray Induced Doppler Shift Attenuation (GRIDSA) Method presented here is applied to the measurement of very short lifetimes, in the femtosecond range. It allows determining the nuclear lifetime by measuring the Doppler shift of a gamma ray emitted from the state of interest, in different directions with respect to a coincident preceding gamma ray, populating the same state and inducing a recoil of the nucleus in the target material with velocities of the order of 10^4-10^5 m/s. We realized an experiment in order to test the GRIDSA technique for the measurement of fs lifetimes after (n,γ) reactions. The measurement was performed at the Institut Laue-Langevin (ILL) with the 8 Ge-clover detectors of the FIPPS array. Preliminary results are discussed.

1. Introduction

It is well known that lifetime measurements allow us to extract fundamental information on the nature of the excited states of a nuclear system [1]. The lifetimes associated to gamma decay span many orders of magnitude, consequently a number of different experimental techniques has been developed. Each one of these is more appropriate for a particular range of lifetimes and/or a particular range of nuclei. The Gamma-ray Induced Doppler Shift Attenuation (GRIDSA) Method presented here is applied to the measurement of very short lifetimes, in the femtosecond range.

Since many years the attenuation of Doppler shift and broadening has been used in gamma spectroscopy to study very short lifetimes of nuclear states. In this context one of the most popular techniques is the Doppler Shift Attenuation Method (DSAM). In its application the interaction of accelerated ions with target nuclei generates recoiling ions with high velocity (several percent of c). The DSAM is used for measuring lifetimes in the 10^{-13} s < τ < 10^{-15} s interval.

Actually, the Gamma-Ray Induced Doppler Broadening (GRID) has been also used to measure lifetimes since a long time. This technique was developed at the Institut Laue Langevin (ILL) in Grenoble, making use of the ultra-high resolution double flat crystal spectrometers GAMS [2]. The GRID technique is based on observing Doppler broadened line shapes of gamma-rays after (n,γ) reactions. In this case the Doppler broadening is induced by a preceding gamma ray, the energy of the nuclear recoil is small (several hundreds of eV only). Nuclear state lifetime can be extracted when comparing these line shapes to computer simulations of the atomic slowing down. However, some features limit its applicability, for example: it requires massive samples (several grams), strong de-

IOP Conf. Series: Journal of Physics: Conf. Series **1023** (2018) 012005 doi:10.1088/1742-6596/1023/1/012005

excitation transitions and a good knowledge of the complete feeding scenario populating the level of interest. These limitations are not present in the Gamma-ray induced Doppler shift attenuation (GRIDSA) method, which is described in the next section.

2. The GRIDSA Method

The GRIDSA method [3] shares the same basic principles with the GRID technique, however in this case the Doppler- shift instead of -broadening is measured. In its application, following a (n,γ) reaction, a primary gamma ray with energy E_γ is emitted and consequently (for momentum conservation) the emitting nucleus must recoil in the opposite direction. Considering a simple two-step cascade to the ground state, the second emitted gamma ray can be Doppler shifted. This Doppler shift is the result of two effects on different time scales: the lifetime of the nuclear state the atomic time scale of the slowing down of the recoiling atoms in the lattice of the target material. One of these two features must be known in order to extract the other. In the present case, we aim to extract information on the nuclear level lifetime and the slowing down process of the nuclei in the target can be simulated starting from some physical assumptions on the type of collisions and interaction between atoms, and generating a velocity trend, as a function of time.

We applied the GRIDSA method using an array of 8 Ge-clover detectors: the FIPPS array operated at the ILL laboratory [see panel a) of figure1]. Let's consider gamma rays of a two-step cascade, where the level of interest (i.e. the one of which we are interested in measuring the lifetime) is between the two transitions. For the second among these two gamma rays in cascade, the events, which contribute to the peak can be separated in different spectra on the basis of the emission angle between the first and the second Ge-clover detector that fired in coincidence, then the shift between the peak of each spectrum and a reference peak that it is not Doppler shifted is measured. This difference is expected (provided that the lifetime of the level of interest is sufficiently short) to follow the trend illustrated in the panel b) of figure 1 and it is given by the formula: $\Delta E_{\gamma 2} \approx E_{\gamma 2} \cdot v_R/c \cdot \cos(\theta)$. Provided to have sufficient statistics, a way to improve the angular resolution consists in using the position information associated to the single crystals inside the clover. The centres of the crystals in the same clover can be at 24 degrees in case they are one next to each other, or at 35 degrees if they are on the diagonal. In this way the granularity in the angular coordinate improves and the curve indicated in the panel b) of figure 1 can be sampled with more experimental points.

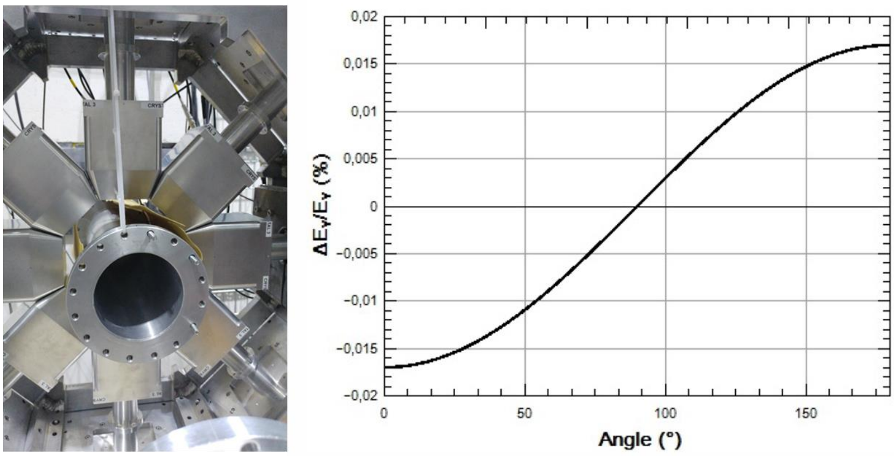

Figure 1. Panel a): picture of the 8 clover HPGe detectors of the FIPPS array operated at ILL. Panel b): Representation of the expected Doppler shift divided by the energy of the second gamma ray emitted, as a function of the angle between the first and the second gamma ray.

IOP Conf. Series: Journal of Physics: Conf. Series **1023** (2018) 012005 doi:10.1088/1742-6596/1023/1/012005

3. Experimental test of the GRIDSA and Preliminary Results

We proposed an experiment in order to test the GRIDSA technique to measure fs lifetimes after (n,γ) reactions. The experiment was performed in January 2017 at ILL with the 8 clover detectors of the FIPPS array [see panel a) of figure 1]. Different targets were used in order to scan over a certain range of isotope masses, lifetimes and recoil velocities. We present here preliminary results associated with the case of NaCl target. The studied case is the one of levels in the ^{36}Cl isotope, recoiling in the target after the reaction ^{35}Cl(n,γ)^{36}Cl realized with thermal neutrons. The maximum shift induced by the Doppler effect was expected to be ~0,5 keV, with v_R=5,1·104 m/s, (maximum velocity, when the nucleus begins to recoil).

In particular the first studied cascade was the one that, from the capture level at 8580 keV, de-excites the nucleus to the ground state with two gamma rays of 5715keV and 2864keV [figure 3 panel a)]. This case was chosen because the mean lifetime of the intermediate state is very short (about 23fs), the first gamma ray is rather energetic, so it can induce a sufficiently relevant recoil of the nucleus, and the second gamma ray is also rather energetic; in fact, the energy shift that we want to measure depends linearly on the energy of the second gamma ray. Moreover, the second gamma ray has to be emitted in the very short period of time in which the nucleus is still recoiling ($\sim 10^{-13}$s). A shift was therefore expected to be observed and, in fact, comparing the peaks relative to the events in which the two Ge-clover detectors that fired in coincidence are at 45 deg and 135 deg respectively [see figure 2 panel a)], a separation between the centroids is clearly visible as it is shown in the spectra of the panel b) in figure 2. As expected the 2864 keV peak is shifted towards lower energies in the case the two Ge-clover detectors that fired have a smaller relative angle (45 deg), since in this case the ^{36}Cl nucleus is recoiling moving away from the crystal that detected the 2864 keV gamma ray. The opposite is true for the case of the two Ge-clover detectors having a larger relative angle of 135 deg.

The centroids of the 2864 keV peak were calculated for each gamma spectrum obtained imposing a gating condition on the angle between the two HPGe crystals that fired in coincidence (detecting respectively the 2864 keV and the 5715 keV gamma rays from the excited ^{36}Cl nucleus). These centroids are plotted as a function of the angles between the two HPGe crystals in the plot displayed in the panel b) of figure 3. The trend obtained reflects that expected from the calculated curve shown in the panel b) of figure 1.

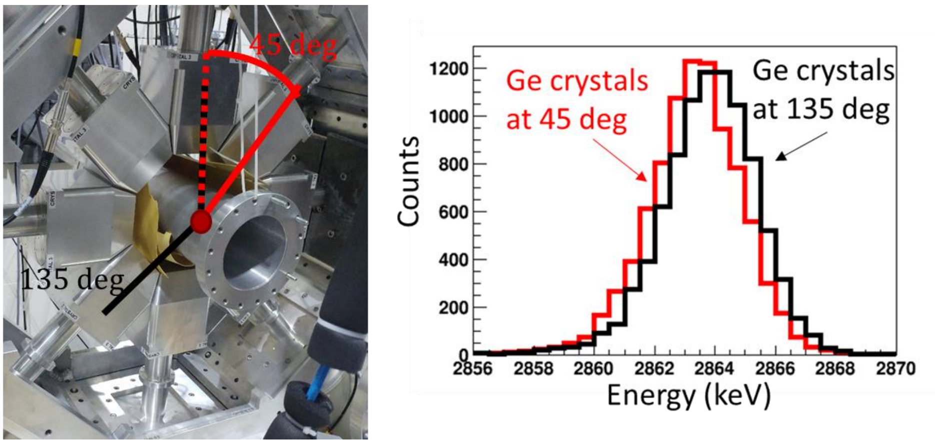

Figure 2. Panel a): picture of the 8 clover HPGe detectors of the FIPPS array operated at ILL. Panel b): peaks relative to the events in which the two Ge-clover detectors that fired in coincidence are at 45 degrees and 135 degrees respectively, a separation between the centroids is clearly visible.

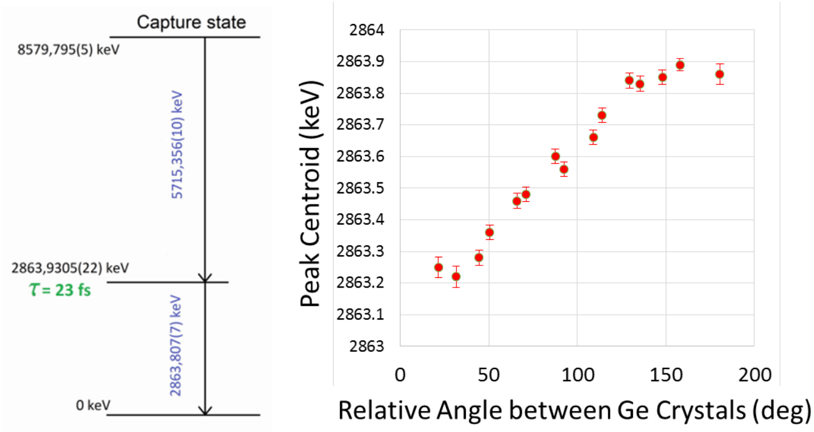

Figure 3. Panel a): Scheme of the 2-step transition trough the intermediate state of 2864 keV , with short mean lifetime: τ = 23fs. Panel b): the centroids of the 2864 keV peak plotted as a function of the angle between the two HPGe crystals that fired in coincidence.

However, in order to extract quantitative information on the nuclear level lifetimes the slowing down process of the recoiling nuclei in the target has to be under control. A simulation was performed using the SLOWDOWN code [4]. In the model the nuclei are considered to be placed in a lattice. After the neutron capture reaction the nucleus emits a high-energy gamma ray, which induces the nucleus itself to recoil. Then the nucleus gradually slows down, due to the interaction with the other atoms in the lattice. During this slowing down process other gamma rays can be emitted. This simulation allows us to obtain a velocity distribution at an instant of time corresponding to the decay time of the considered nucleus. This is shown in figure 4. The next step (which is not yet completed since the data analysis is still ongoing) consists of using the results of this simulation to produce calculated data to be compared with the experimental ones (e.g. like those displayed in the panel b) of figure 3) and then extract the measured value of the lifetime.

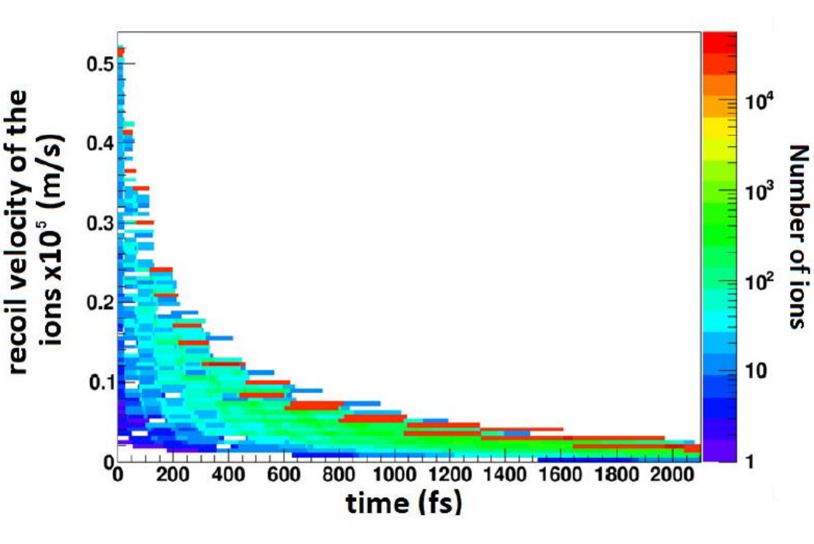

Figure 4. Two-dimensional histogram representing the simulated recoil velocity as a function of time for the case of ^{36}Cl nuclei: the different colors represent the probability, expressed in number of ions with a particular velocity at a specific instant of time.

References

[1] Nolan P J and Sharpey Schafer J 1979 Rep. Prog Phys 42 1
[2] H.G. Börner and J. Jolie, J. Phys. G 19 (1993) 217.
[3] T. Khan, T. von Egidy, F.J. Hartmann, J. Ott, M. Jentschel, Nucl. Instr. Meth. A 385 (1997) 100-107
[4] M. Jentschel, *Description of SLOWDOWN*, private communication.