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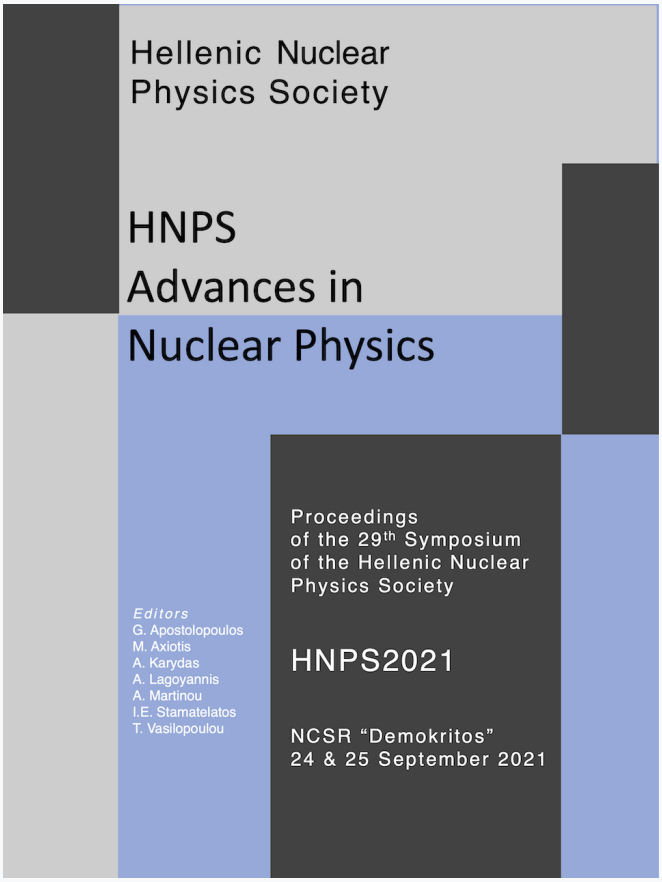

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Temperature-dependent relative self-absorption measurements in ^{27}Al

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Abstract Nuclear resonance fluorescence measurements provide direct sensitivity to ground-state transition widths by probing the photoexcitation process of nuclear resonances. A technique in Relative Self-Absorption (RSA) measurements, in which measurements are done at multiple absorber temperatures, was developed, and tested with ^{27}Al at the Darmstadt High Intensity Photon Setup of the Superconducting Darmstadt Linear Accelerator. The advantage of this technique, over the regular RSA, is the possibility to overcome the need for theory input on the effective temperatures and the uncertainties that they introduce in the measured level widths. The technique and the preliminary results of the first test-measurements are presented in these proceedings.

Keywords nuclear resonance fluorescence, temperature-dependent relative self-absorption, level width, ^{27}Al, DHIPS@S-DALINAC

INTRODUCTION

Recent state-of-art ab-initio calculations are giving very sensitive results of key observables for the understanding of the nuclear forces. The impact of the effective two-body contributions to transition operators was proved in Ref. [1]. This was possible because of the very precise measurement of the half-life of the state of interest, in the range of attosecond. This shows the importance of measuring nuclear observables with high precision.

Nuclear Resonance Fluorescence (NRF) measurements [2,3,4] provide insight into several nuclear observables related to the transition strengths. In NRF the measured quantity is related both to the excitation and the de-excitation process of the nucleus. The measured quantity is a product of the ground state transition width (Γ_0) and the branching ratio of the corresponding decay channel, $\sim\Gamma_0\cdot\Gamma_j/\Gamma$ (with Γ_j the level's transition width and Γ the total width of the level). In recent years another technique, the Relative Self-Absorption (RSA) [2,4], has been used at Technische Universität Darmstadt [1,5,6]. In RSA the measured quantity is only related to the excitation process, $\sim\Gamma_0$. So, one has access directly to the transition probability of the level ($\Gamma_0 \propto B(\lambda L)$).

In RSA two targets consisting of the isotope of interest are used, a thick absorber and a thin scatterer. Two measurements are performed, one without the absorber in front of the scatterer and one with it in place, see Fig. 1. The de-excitation rate of the nuclear level of interest of the scatterer is measured in the two measurements. The self-absorption, R, between the two measurements, after normalization to a reference isotope for the non-resonance scattering of the beam into the absorber, can be described by equation (1).

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$$R = 1 - \frac{Sc_1}{Sc_2} \cdot \frac{Ref_2}{Ref_1}, \quad (1)$$

where $Sc_{1(2)}$ is the counts on the γ-ray line from the scatterer from the measurement with the absorber (without the absorber) and $Ref_{1(2)}$ is the counts on the γ-ray line from the reference isotope from the measurement with the absorber (without the absorber). In RSA the R is compared with theoretical calculations. By this comparison the Γ_0 is derived. The theoretical calculations comprise the calculation of the effective temperatures (T_{eff}) of the targets, that includes corrections due to condensed-matter effects in the target material (see below). These calculations are complicated for chemical compounds. More detailed description of the RSA technique can be found in Refs. [1,6].

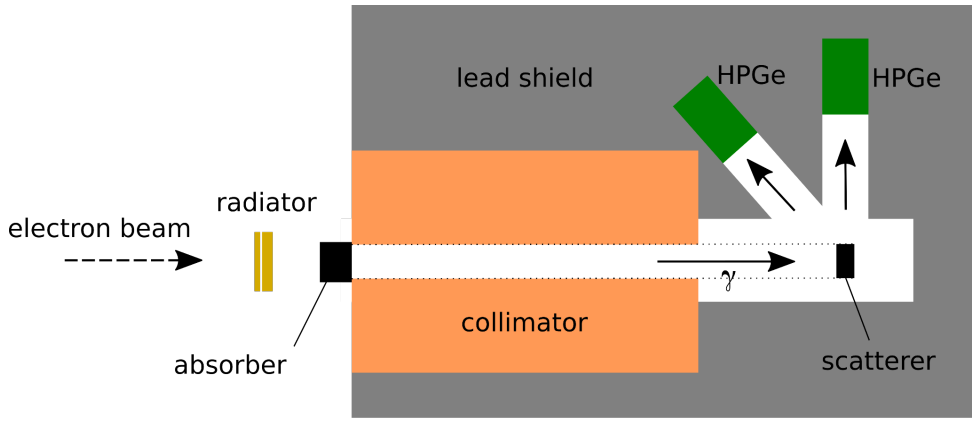

Fig. 1. *Experimental setup. The absorber was fully covering the collimator opening. As it is shown with the dotted lines, the full size of the scatterer target was irradiated by the photon beam. More details about the setup can be found in the text.*

TEMPERATURE-DEPENDENT RELATIVE SELF-ABSORPTION MEASUREMENTS

An advanced RSA technique for level width measurements, the Temperature-dependent Relative Self-Absorption (T-RSA) technique, was developed in the Technische Universität Darmstadt. In it measurements in multiple target temperatures are performed. The advantage of this technique, over the regular RSA, is the possibility to overcome the needed theoretical calculations for the T_{eff} of the targets and in practice the error that they introduce. Allowing for high-precision measurements of the level widths.

Due to the thermal motion of the target nuclei and quantum-mechanical lattice vibrations the nuclear resonance becomes wider in the laboratory frame in comparison to nuclei in rest. The resulting broadened resonance can be described with the Doppler broadened absorption cross section. For targets in different temperatures the Doppler width (Δ) is different. Δ can be described by:

$$\Delta = \sqrt{\frac{2k_B T}{Mc^2}} \cdot E_i \quad (2)$$

with the mass M of the nucleus, the Boltzmann constant k_B, E_i the resonance energy and T the temperature of the target [6]. For solid targets, the temperature T has to be replaced with the

effective temperature T_{eff} which accounts for vibrational degrees of freedom in the lattice of the target material.

According to the Debye theory the T_{eff} can be calculated by the thermodynamical temperature (T) and the Debye temperature (T_D) from equation (3). In Fig. 2 the equation (3) is plotted for ^{27}Al (T_D=390 K [7]). For very low temperatures (approaching the absolute zero (0 K)), the T_{eff} becomes 3/8 of the T_D. In very high temperatures the T_{eff} converges towards T. T-RSA measurements can be performed in high T in order to overcome the need of any theoretical calculation for the T_{eff} in the determination of the level width. As well, T-RSA measurements can be performed in multiple temperatures in order to measure the T_D of the material.

$$T_{eff} = 3T \cdot \left(\frac{T}{T_D}\right)^3 \int_0^{\frac{T_D}{T}} t^3 \cdot \left(\frac{1}{e^t + 1} + \frac{1}{2}\right) dt \quad (3)$$

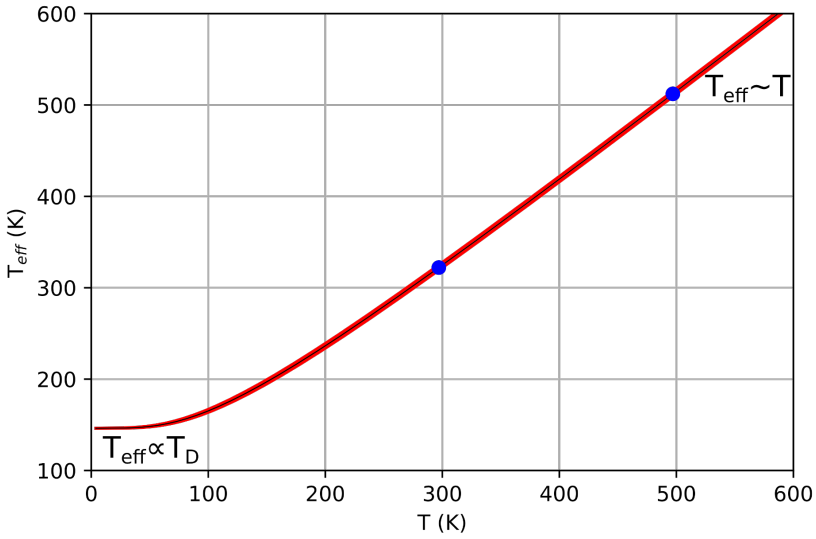

Fig. 2. *The T_{eff} calculated from the Debye theory, equation (3), for ^{27}Al (T_D=390 K [7]) (black curve). With red the uncertainty band is shown for an uncertainty of 3 K on T. The two blue dots represent the absorber's temperatures in the experiment performed at DHIPS.*

In the test experiment described below, measurements in two absorber temperatures were performed in ^{27}Al, at room temperature (~297 K) and at 493 K. The goal of the experiment was to observe the effect of the different absorber temperatures in the absorption in it. This effect can be observed by equation (1) where, in this case, $Sc_{1(2)}$ is the counts on the γ-ray line from ^{27}Al from the measurement at room temperature (at 493 K) and $Ref_{1(2)}$ is the counts on the γ-ray line from the reference isotope from the measurement at room temperature (at 493 K).

EXPERIMENT

T-RSA measurements in ^{27}Al were performed at the Darmstadt High Intensity Photon Setup (DHIPS) [8] of the Superconducting Darmstadt Linear Accelerator (S-DALINAC) [9, 10]. An electron beam, at 5.4 MeV and with a current of approximately 30 μA, was stopped in

the bremsstrahlung target (radiator) consisting of a 0.5mm- and a 2.5mm-thick gold foils. The energy end point of the continuous-energy photon beam generated, by bremsstrahlung processes, was 5.4 MeV. The photon beam was collimated by a 1 m long copper collimator with a 2 cm diameter opening. The collimated photon beam was irradiating the scatterer which was placed in the end of the collimator. The scatterer was composed of 5 mg of ^{27}Al and 0.4 mg of ^{11}B. Its diameter was 2 cm. The full size of it was irradiated by the photon beam. The setup can be seen in Fig. 1.

Two HPGe detectors were used in order to measure the de-excitation of the scatterer. The scatterer and the two detectors were surrounded by lead shielding to protect the measurement from background signals. One of the detectors was placed at 90° and the other at 130° with respect to the beam axis. Appropriate filters, lead and copper plates, were placed in front of the detectors to optimize their count rates and suppress the low energy part of the gamma spectra. The energies of the gamma rays of interest in the experiment were all larger than 2000 keV. The efficiency and energy calibration of the setup were made with a ^{56}Co, a ^{60}Co and a ^{152}Eu source. The ^{56}Fe(p,n) reaction was used to produce the ^{56}Co source in the Tandem accelerator at the Institut für Kernphysik of the Universität zu Köln. It was used because of its high-energy gammas (up to 3.5 MeV). The activity of this source was not known with good accuracy (~3.5 MBq), so the efficiency calibration was made relative to the other two sources.

Measurements with the absorber in two temperatures were performed, at room temperature (297 K) and at 493 K. The absorber was heated at 493 K with a heating device constructed by two positive temperature coefficient (PTC) plates (see Fig. 3). The temperature of the absorber was measured during the experiment with a PT-100 temperature sensor which was inserted in it. The temperature of the absorber was 297±3 K during the room temperature measurement and 493±3 K during the high temperature measurement. The homogenized heating of the absorber was tested and verified in the lab before and after the experiment by measurements with multiple temperature sensors inserted in it. The heating device, with the absorber placed between the two heating plates, was placed in front of the collimator opening, see Fig. 3. In the figure the radiator (the bremsstrahlung targets), the beam hardener (a copper plate), for the absorption of the X-rays produced from the radiator, and the electron-beam pipe can also be seen.

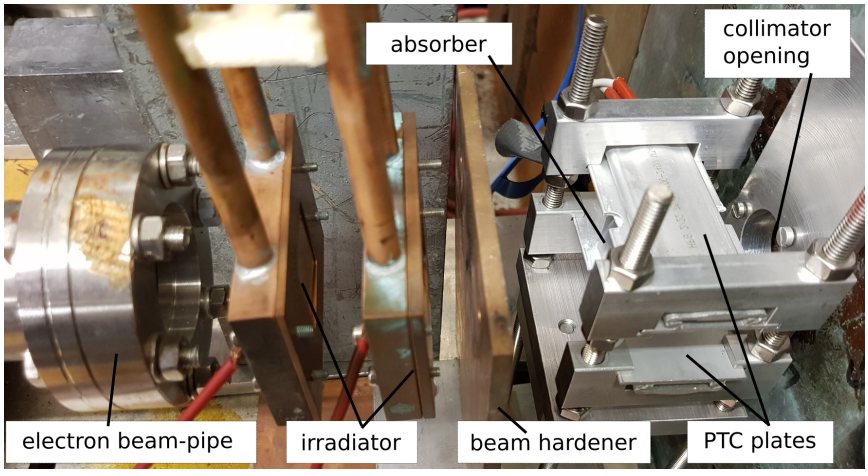

Fig. 3. *Experimental setup in front of the DHIPS collimator.*

RESULTS AND DISCUSSION

In Fig. 4 the on-line spectra from the detector at 90° is shown for the two measurements. For comparison, the measurement with the absorber at room temperature was normalized to the one at 493 K by using the known internal γ-ray transitions of ^{11}B at 2124 keV. The gamma at 2212 keV corresponds to the decay of the (7/2$^+$) excited state to the ground state in ^{27}Al, its level width is 17.19 (31) meV [2]. The close energy of the two γ-rays allows, for the purposes of this proceedings, the comparison of the two measurements after the normalization. No energy-dependent corrections are taken into account. One can see the larger activation of the scatterer in the case of the high temperature measurement.

The ries code [11], a python library for the estimation of photonuclear reaction rates in low-energy nuclear physics experiments, was used in order to perform theoretical calculations for the higher gamma-absorption expected in the scatterer when the absorber was at 493 K. The calculations resulted in R=0.045, see equation (1). In the on-line analysis of the experiment the R was measured with an error of less than 50%. This accuracy will allow the observation of the effect in the performed experiment, in which the temperature difference between the two measurements was ~200 K. In the future T-RSA measurements with larger temperature differences are planned at DHIPS.

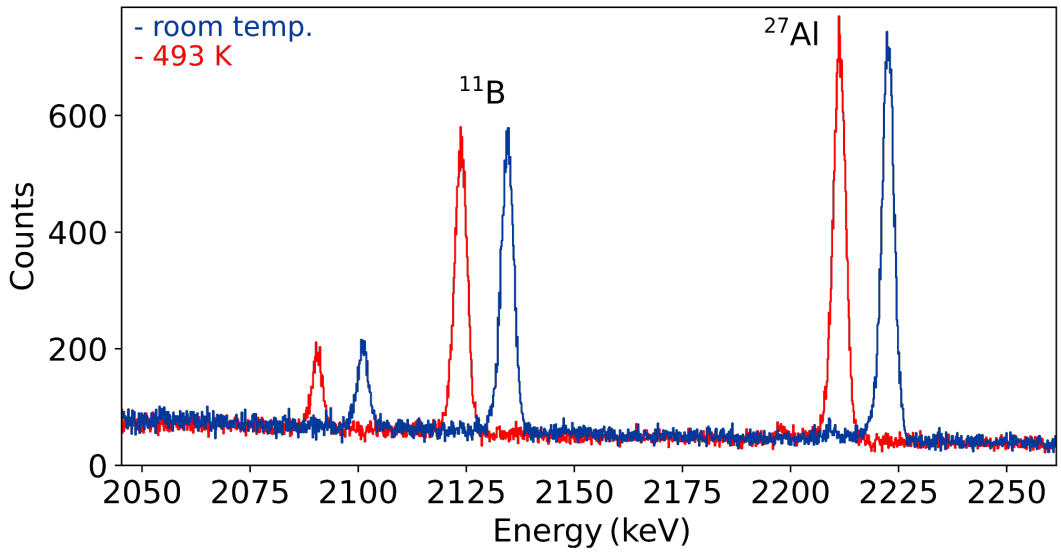

Fig. 4. *Spectra of the HPGe detector at 90° from the measurement at room temperature (blue) and at 493 K (red). For better visibility, the blue spectrum was shifted to higher energies. The ^{11}B transition was used to normalize the spectrum from the measurement at room temperature so that the difference in counts for the ^{27}Al transition is due to self-absorption only. The spectra are the on-line spectra.*

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