Nuclear Resonant Reflectometry of Thin Films by Stroboscopic Detection of Synchrotron Radiation

Here we report on the first grazing incidence synchrotron Mössbauer study in energy domain [1]. The experiments were performed on ^{57}Fe-containing thin films using the recently developed stroboscopic detection scheme [2,3].

Nuclear resonant scattering (NRS) of synchrotron radiation (SR) became an established nuclear hyperfine method in the last two decades [4]. NRS of SR in the forward direction is conventionally recorded as a beating time response of the nuclear ensemble following a short resonant synchrotron pulse. The beat frequencies are characteristic of the hyperfine fields.

In grazing incidence, the interferences of the SR plane waves reflected from different surfaces or interfaces of a stratified sample result in an angle-dependent reflectivity and strong depth selectivity. By recording the prompt electronic and the delayed nuclear resonant reflectivity curves, both the chemical and the hyperfine depth profile can be probed with nanometer-scale resolution. Grazing-incident NRS of SR is commonly called Synchrotron Mössbauer Reflectometry (SMR) [4,5].

The feasibility of the stroboscopic detection (SD) scheme for NRS of SR was first demonstrated in the forward direction [2]. In an SD experiment, two samples, the investigated one and a vibrating reference absorber coherently scatter the SR. The signal is recorded in a 2D array as a function of both the time elapsed after the SR pulse and the velocity v of the reference absorber. As an advantage, SD of NRS of SR provides a spectrum in the energy domain [2,3] similar to a conventional Mössbauer spectrum.

In the forward scattering geometry, the prompt electronic scattering homogeneously contributes to the stroboscopic spectrum, therefore it does not affect the spectral shape. However, in grazing-incidence, the stroboscopically detected SMR (⇒ SDSMR) line shape considerably differs from the shape of lines in a SD of NRS line in the forward direction due to the coherency of the electronic and nuclear scattering. The description of the time-domain SMR [4] was recently extended to evaluate stroboscopic spectra [1]. The code was merged into the EFFINO program [4] and used in the data evaluation below.

In the experiments performed at beamline **BL09XU**, SDSMR was applied for the first time. The experiments were performed in 203-bunch mode, which corresponds to a ~24 ns bunch separation time. ^{57}Fe-containing isotopic and magnetic multilayer samples were investigated using the 14.4 keV Mössbauer transition of ^{57}Fe nuclei. The experimental setup is shown in Fig. 1. Prompt X-ray and delayed nuclear reflectivity curves, as well as SDSMR spectra were recorded using three 2-ns dead-time Hamamatsu avalanche photodiodes (APD) in series. The velocity range of the reference absorber on the Mössbauer drive was v_{max} = ±20 mm/s. The 1024×1024 channel SDSMR data were time-integrated using appropriate time windows of 8 ns period and 4 ns length [2,3].

In Fig. 2, prompt electronic (a) and delayed nuclear (b) reflectivity curves as well as SDSMR spectra (c) to (e) are shown for a glass/$[^{56}Fe / ^{57}Fe]_{10}$ isotopic multilayer saturated in a transversal magnetic field. The peak in the delayed reflectivity at the total reflection angle in panel b) is a special feature of SMR (e.g. [4], p. 427). In panels (c) to (e), the four resonance lines of the +1 and –1 stroboscopic orders (right and left side, respectively), partially overlap with the 0th order in the middle. The delicate interplay between electronic and nuclear scattering is demonstrated by considerably different SDSMR spectra (c) to (e) at only slightly different angles near the total reflection angle. The full lines are simultaneous least-squares fit.

Figure 3 shows a similar set of spectra of ^{57}Fe/Cr

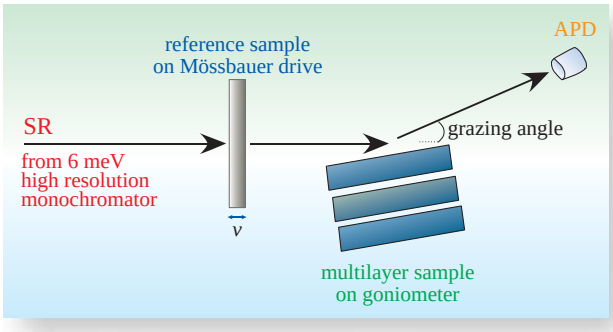

Fig. 1. Experimental setup for stroboscopically detected synchrotron Mössbauer reflectometry.

antiferromagnetically coupled epitaxial multilayer prepared on a MgO(001) substrate. Stroboscopic spectra are shown at the angles of total reflection, the antiferromagnetic (AF) and the structural Bragg peaks, (c) to (e), respectively. Continuous lines are simultaneous fits to a model structure of $[^{57}Fe(2.6\ nm)/Cr(1.3\ nm)]_{20}$ with Fe magnetizations parallel/antiparallel to the wave vector along the in-plane Fe (100) easy axis. This alternating longitudinal hyperfine field in consecutive Fe layers is justified by the fit.

In conclusion, we have demonstrated that, synchrotron Mössbauer reflectometry of ^{57}Fe-containing thin films is feasible in the energy domain by using the stroboscopic detection scheme.

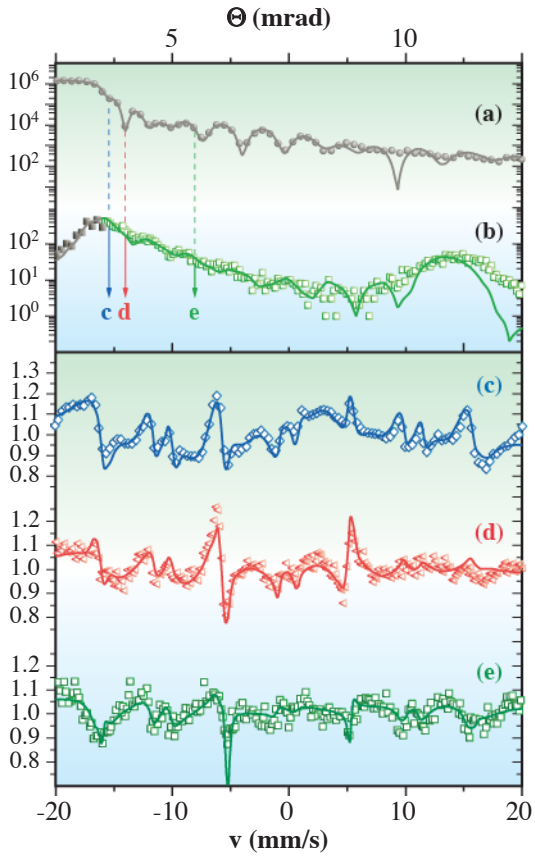

Fig. 2. Prompt electronic **(a)** and delayed nuclear **(b)** reflectivity curves and SDSMR spectra **(c)** to **(e)** of a $[^{56}Fe/^{57}Fe]_{10}$ isotopic multilayer at grazing angles indicated by the arrows.

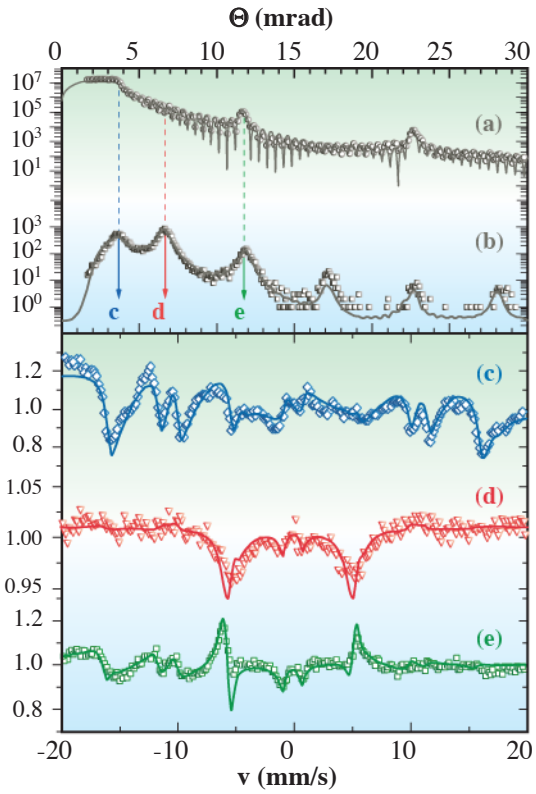

Fig. 3. Prompt electronic **(a)** and delayed nuclear **(b)** reflectivity curves and SDSMR spectra **(c)** to **(e)** of $[^{57}Fe\ (2.6\ nm)/Cr\ (1.3\ nm)]_{20}$ at various angles indicated by arrows.

László Bottyán[a], László Deák[a] and Romain Coussement[b]

(a) KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
(b) Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, Belgium

E-mail: deak@rmki.kfki.hu

References

[1] L. Deák, L. Bottyán, R. Callens, R Coussement, M. Major, S. Nasu and Y. Yoda: to be published in Phys. Rev. B.
[2] R. Callens *et al.*: Phys. Rev. B **65** (2002) 160404(R).
[3] R. Callens *et al.*: Phys. Rev. B **67** (2003) 104423.
[4] E. Gerdau and H. de Waard: Hyperfine Interact. **123-125** (2000) reviews and references therein.
[5] L. Deák *et al.*: Physica B **297** (2001) 113.