Hyperfine Interact
DOI 10.1007/s10751-011-0444-z

Time-domain interferometry experiments using multi-line nuclear absorbers

Makina Saito · Makoto Seto · Shinji Kitao · Yasuhiro Kobayashi · Masayuki Kurokuzu · Yoshitaka Yoda

Abstract The microscopic slow dynamics in various samples has been studied by a time-domain interferometry (TDI) method using nuclear resonant scattering (NRS) of synchrotron radiation and an improvement of the efficiency of TDI is highly desired. To realize it, we developed the TDI method using α-Fe foils with multi-line Mössbauer spectra as nuclear absorbers. Compared to the conventional TDI method using single-line Mössbauer absorbers, the reduction of the measuring time is expected by a simulation study. The simulation study shows a comparatively large change on the multi-line TDI time spectra by the diffusion in a sample and indicates much improvement of the efficiency. We obtained time spectra of the multi-line TDI and the obtained quasi-elastic broadening values of NRS energy width obtained by fitting the time spectra were confirmed to be close to the values obtained by the conventional TDI and estimated standard deviations by the multi-line TDI were comparatively small as expected by the simulation study.

Keywords Nuclear resonant scattering · Time-domain interferometry method · Slow dynamics · Liquid crystal

The microscopic slow dynamics with a time scale of around 100 ns has attracted much interest in the various scientific areas. To study it, a time-domain interferometry (TDI) method using nuclear resonant scattering (NRS) of synchrotron radiation

M. Saito · M. Seto · S. Kitao · Y. Kobayashi · M. Kurokuzu
Research Reactor Institute, Kyoto University, Osaka 590-0494, Japan

M. Saito (✉) · M. Seto · S. Kitao · Y. Kobayashi · M. Kurokuzu · Y. Yoda
CREST, Japan Science and Technology Agency, Saitama 332-0012, Japan
e-mail: seto@post3.rri.kyoto-u.ac.jp

Y. Yoda
Japan Synchrotron Radiation Research Institute, Hyogo 679-5198, Japan

Published online: 23 November 2011

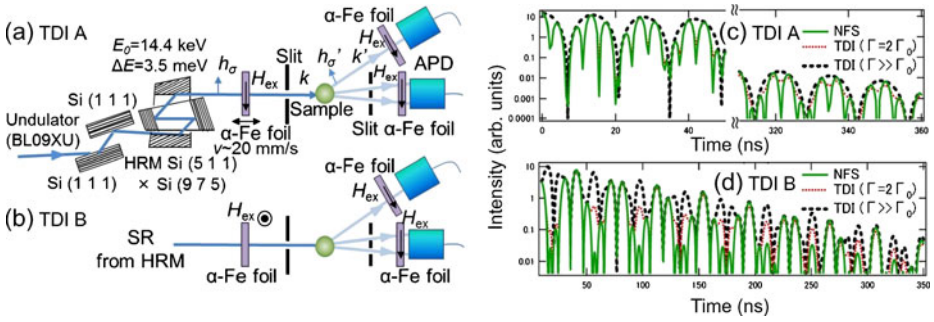

Fig. 1 Experimental setups of **a** TDI A and **b** TDI B, and the time spectra of **c** TDI A and **d** TDI B calculated under some conditions shown in the text

(SR) has been developed by using the ^{57}Fe first excited state, which has the natural energy-width Γ_0 of 4.6 neV [1]. After that, TDI method has been applied to study on for example, an ionic liquid [2]. In order to improve the efficiency, we used α-Fe foils having hyperfine splitting Mössbauer spectra as nuclear absorbers of TDI. Compared to the conventional TDI using single-line nuclear absorbers, the multi-line TDI method, whose set ups are shown in Fig. 1a and b (explained later), is expected to reduce a measuring time because intensity of nuclear forward scattering (NFS) from each nuclear absorber is shown by a simulation study to be increased by using thicker nuclear absorbers for the new TDI without a decrease of efficiency [3]. By considering the principal of TDI method, TDI time spectra changes from the time spectra calculated by the coherent sum of NRS electric fields from two absorbers to the time spectra calculated by the incoherent sum of them with increasing the degree of a diffusion in a sample due to the destroy of phase correlation of NRS by the diffusion in a sample as explained for the case of the conventional TDI [1]. Similar change could be confirmed for the case of the multi-line TDI: As shown in Fig. 2, calculated time spectra of TDI ($\Gamma = 2\Gamma_0$) relax from NFS time spectra (or TDI ($\Gamma << \Gamma_0$)) to the time spectra of TDI ($\Gamma >> \Gamma_0$), which is identical with the time spectra calculated by the incoherent sum of NRS from two absorbers, where Γ is the quasi-elastic broadening of the line width of NRS. The significant difference between NFS time spectra (or TDI ($\Gamma << \Gamma_0$)) and the time spectra of TDI ($\Gamma >> \Gamma_0$) of the multi-line TDI compared to the change of the conventional TDI is expected to cause much improvement of efficiency, which is numerically estimated by the simulation study [3]. Therefore, demonstrating this new TDI method is thought to be valuable and we report first multi-line TDI experiments in this paper.

The TDI experiments were performed at BL09XU of SPring-8 in Japan. Incident radiation with 3.5-meV energy-width at the nuclear resonant energy of the first excited state of ^{57}Fe was obtained by using a high-resolution monochromator (HRM) shown in Fig. 1. The sample used is a liquid crystal, 4-cyano-4′-octylbiphenyl (8CB). TDI measurements with two different experimental setups were attempted by changing the directions of the external magnetic field to α-Fe foils as follows: in the setups "A" shown in Fig. 1a, the external magnetic fields $\boldsymbol{H}_{ex}$, whose directions are parallel to the directions of the magnetic field vector of SR $\boldsymbol{h}_\sigma$ and perpendicular to the wave vectors of incident SR $\boldsymbol{k}$, were applied to upstream α-Fe foils, showing 2-line energy spectra in this condition. The upstream α-Fe was driven with a constant

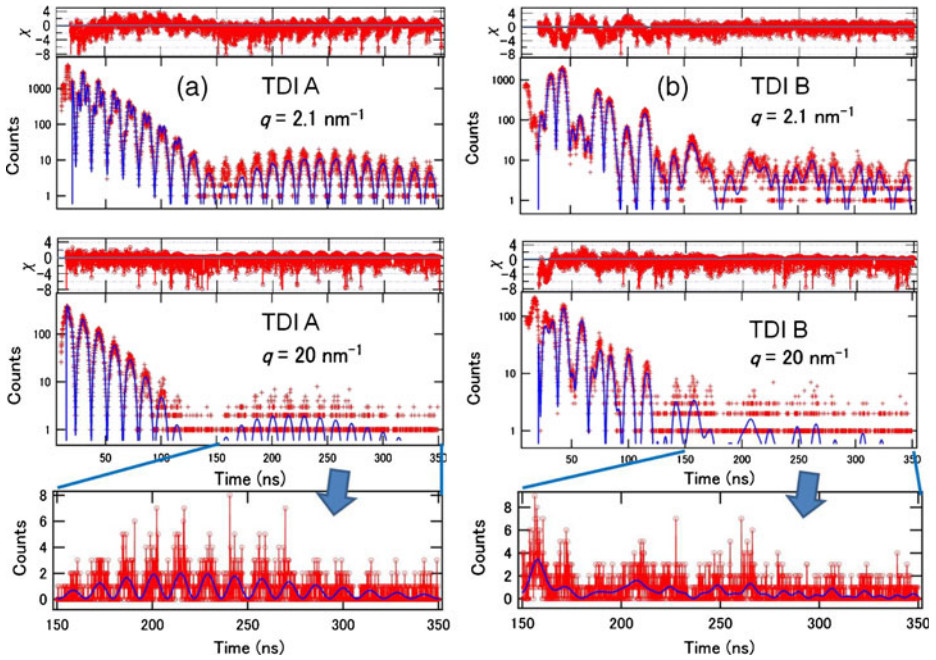

Fig. 2 Time spectra of **a** TDI A obtained at $q = 2.1$ and 20 nm^{-1} and **b** TDI B obtained at $q = 2.1$ and 20 nm^{-1}. Solid lines show fitting curves and χ (=(sim.-exp.)/sim.^0.5) of the fitting results are shown

speed of about 20 mm/s. The external magnetic fields were also applied to the downstream α-Fe foils in the same manner with respect to scattered $\boldsymbol{k}$' and $\boldsymbol{h}_\sigma$', and they were not driven. On the other hand, as shown in the setups "B" in Fig. 1b, $\boldsymbol{H}_{\rm ex}$ perpendicular to $\boldsymbol{k}$ and $\boldsymbol{h}_\sigma$ were applied to the upstream α-Fe foils, showing 4-line energy spectra, while the $\boldsymbol{H}_{\rm ex}$ perpendicular to $\boldsymbol{k}$' and parallel to $\boldsymbol{h}_\sigma$' were applied to the downstream α-Fe foils, showing 2-line energy spectra. Here, all α-Fe foils were not driven. Magnetic circuits composed by permanent magnet pieces were used to apply magnetic fields of about 0.2 T. Two sets of multi-element avalanche photo diode (APD) detectors were arranged at positions with a momentum transfer q of 2.1 and 20 nm^{-1}. Obtained TDI time spectra of setups "A" and "B" for 6 h at 299.8 K at each q are shown in Fig. 2a and b, respectively. In this temperature the 8CB is under smectic A phase. The expected changes shown in Fig. 1c and d could be confirmed in the obtained TDI time spectra shown in Fig. 2.

Obtained time spectra were fitted by MOTIF [4] modified to analyze TDI time spectra by taking account of the quasi-elastic broadening Γ of the line width of NRS from upstream α-Fe by 8CB as discussed following paper in detail [3], and all time spectra were successfully fitted by using a Lorentz function for the quasi-elastic broadening of NRS as shown in Fig. 2 [5]. The obtained Γ values at $q = 2.1$ and 20 nm^{-1} in the unit of Γ_0 are 0.379(25) and 6.29(51) for TDI A, and 0.340(5) and 6.53(37) for TDI B, respectively. The obtained Γ values by the multi-line TDI experiments were confirmed to be close to the values of 0.328(64) and 9(22) by the conventional TDI experiments with the same measuring time. There are deviations

to some extent in the fittings as shown in Fig. 2, which may cause systematic errors of obtained Γ values, though obtained Γ values by the new TDI are not concluded to be inconsistent (or consistent) each other. To fit the spectra better, for example checking of homogeneity of the absorbers may be necessary. Obtained comparatively small σ_Γ values of new TDI could be explained by the simulation study and relatively large σ_Γ value obtained by the conventional TDI at $q = 20\ \mathrm{nm}^{-1}$ could be explained by a low quality of the time spectra originating from the comparatively low NRS intensity of the conventional TDI (about 0.26 times compared to that of TDI B). In conclusion, we could obtain the time spectra of the multi-line TDI in the two experimental setups and the multi-line TDI method is expected to enable further study on microscopic dynamics in the near future by further developments.

Acknowledgements We thank Prof. S. Kishimoto for the development of APD detectors. These experiments were performed with the approval of the Japan Synchrotron Radiation Research Institute (Power User Priority Program No. 2011A0086) and partly supported by the grant-in-aid for Japan Society for the Promotion of Science Fellows.

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