| ESRF | **Experiment title:**<br>Demonstration of parity-time symmetry at x-ray wavelengths | **Experiment number:**<br>HC-4028 |
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**Names and affiliations of applicants** (* indicates experimentalists):
Adriana Pálffy, Xiangjin Kong (Max-Planck-Institut für Kernphysik, Heidelberg, Germany)
Ralf Röhlsberger* (Deutsches Electronen-Synchrotron DESY, Hamburg, Germany)

Report:

In this experiment we have investigated the resonant interaction of x-rays with $^{57}$Fe Mössbauer nuclei embedded in thin-film cavities. The purpose of our experimental campaign was three-fold. First, we attempted to demonstrate for the first time the concept of non-Hermitian x-ray photonics with parity-time symmetry in a thin-film cavity with one embedded $^{57}$Fe layer. Second, we wanted to verify that collective effects such as superradiance can generate unexpected asymmetric hyperfine splittings. To these ends we have investigated thin-film cavities with one embedded $^{57}$Fe layer at different values of external magnetic field induced by the cryostat magnet "George". Finally, third, we aimed at measuring reflectivity spectra at an incidence angle ranging from a cavity resonant angle to off-resonant angles for a thin-film structure with two embedded $^{57}$Fe layers. In this setup we attempted to observe and quantify the transition from a regime mimicking electromagnetically induced transparency to the so-called strong-coupling or Autler-Townes regime. For all three goals, we had prepared several samples and characterized the layer structure at the sputtering facility at DESY, Hamburg. During the experiment we have measured reflectivity spectra at different grazing incidence angles and different values of external magnetic field. The SR beam was stable with no major incidence except for the last shift, where repeated beam dumps jeopardized our last hours of measurement.

One of the crucial features for the experiment was that each spectrum had to be taken at a specific and stable grazing incidence angle. Any instability thereof, in our case even on the level of 0.01° would smear the investigated effect and make its identification in the measured data impossible. At an early stage of the experiment we have noticed that the incident x-ray beam from the Synchrotron Mössbauer Source was not stable over long time intervals. The originally taken spectra over 1-2 hours proved to be useless. Already in our second day of beamtime we have started a procedure of monitoring the incidence angle and taking spectra over smaller time intervals. This procedure was improved such that by the end of the beamtime we had the data acquisition at stable incidence angle under control. Obviously, this required some effort and ingeniosity from the crew.

During the experiment it became clear that all our samples displayed an unexpected strong electric quadrupole splitting. For the samples we had used non-magnetic stainless steel ($Fe_{0.55}Cr_{0.25}Ni_{0.2}$) whose iron content is enriched to 95% with the resonant $^{57}$Fe isotope (later on abbreviated as $^{57}$Fe-SS). Previous experiments (for instance, from beamtime HC-1899 at ERSF) had not revealed that when surrounded in carbon layers, the nuclear resonance displays a strong isotropically oriented quadrupole splitting. Fig. 1 shows a spectrum taken for zero external magnetic field for a thin-film cavity with structure [thicknesses in nm] Pt 3/C 18.5/$^{57}$Fe-SS 0.6/ C 22.5/ Pt 15. The splitting of the peak is very visible. At non-zero magnetic field values, this isotropic quadrupole splitting combines with the magnetic splitting, making the analysis of the experimental data very cumbersome.

Unfortunately, the unexpected presence of the strong quadrupole splitting prevented us from unambiguously identifying the signatures of parity-time symmetry in the x-ray regime. Also, although we had very clean spectra for the cavity with two $^{57}$Fe-SS layers, we could not confirm the electromagnetically induced transparency or the Autler-Townes regimes using established criteria from quantum optics. The data we have taken for one of the thin-film cavities with a single embedded $^{57}$Fe-SS layer was used to prove experimentally the role of superradiance in asymmetric hyperfine splittings. Since in the experiment both (isotropic) quadrupole splittings and magnetic splittings were present, we had to extend our theoretical model to study the effects of superradiance with combined electric and magnetic hyperfine fields. The theoretical model was only recently submitted for publication (see arXiv:2102.11183 [quant-ph]). The data analysis based on that model is already completed and this second manuscript with experimental results is at present under preparation.

The beamtime was a great step further for our thin-film cavity experiments. Knowledge acquired on the behaviour of hyperfine splittings in our samples has led to further research and improvements in the fabrication procedure. With this knowledge, we could design new samples free of unwanted hyperfine splittings and run new experiments in 2020 at DESY, Hamburg, for the two goals that could not be achieved during the ESRF beamtime HC-4028. The one accomplished goal was at the basis of new theoretical model development and one experimental manuscript which is in preparation at the moment.

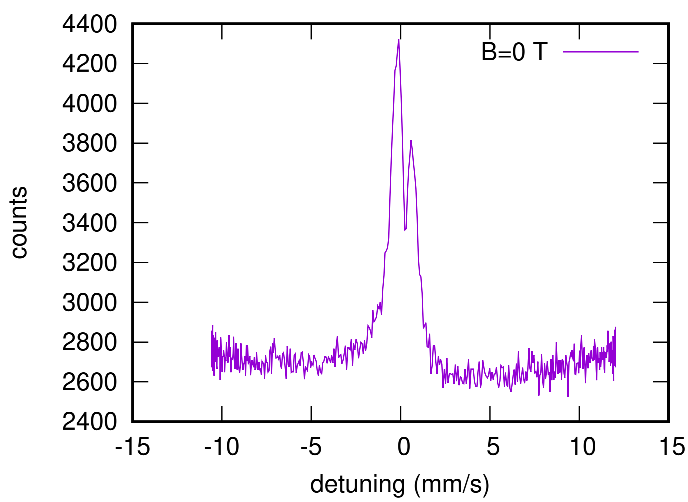


Figure 1: Data set of reflectivity as a function of energy detuning for the cavity structure Pt 3/C 18.5/$^{57}$Fe-SS 0.6/ C 22.5/ Pt 15 and incidence angle driving the third cavity mode. Despite zero external magnetic field, the resonance shows a clear electric quadrupole splitting.