A wave chaotic system with partially violated time-reversal-invariance

Małgorzata Białous[1], Afshin Akhshani[1], Barbara Dietz[2], and Leszek Sirko[1]

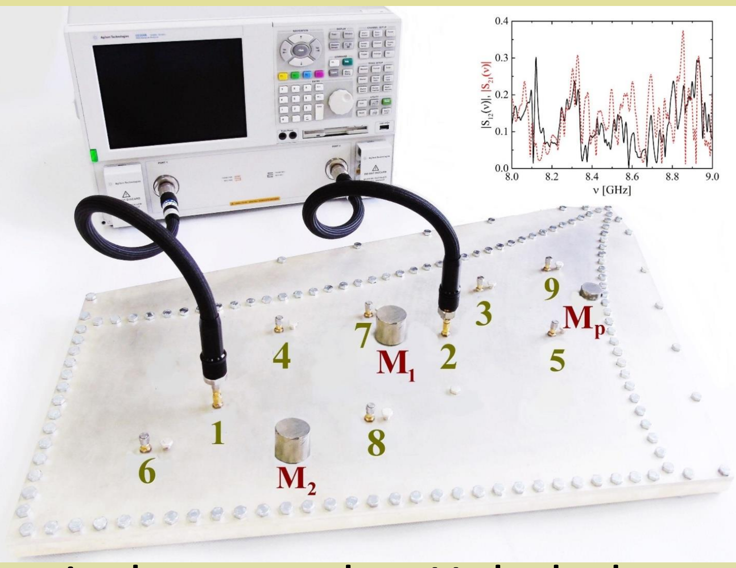
[1]*Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland*

[2]*Lanzhou Center forTheoretical Physics and the Gansu Provincial Key Laboratory of Theoretical Physics, Lanzhou University, Lanzhou, Gansu 730000, China*

INTRODUCTION

We show experimentally and confirm theoretically that above a certain size of $\mathcal{T}$-invariance violation (TIV) the increase of the openness of a wave chaotic system can lead to an increase of the elastic enhancement factor (EEF). In the experiment a quantum billiard with partially violated time-reversal invariance, characterized by the $\mathcal{T}$-invariance violation parameter $\xi \in [0,1]$, is simulated with a flat quarter-bow-tie microwave cavity. TIV was induced by two cylindrical ferrites magnetized by an external magnetic field. The elastic enhancement factor $F_M(\eta, \gamma, \xi)$ is investigated as a function of internal absorption γ and openness η. In these investigations we focus on the frequency range of strongest TIV where the increase of the number of open channels M causes a boost of the elastic enhancement factor, instead of the expected lowering [1,2].

EXPERIMENT

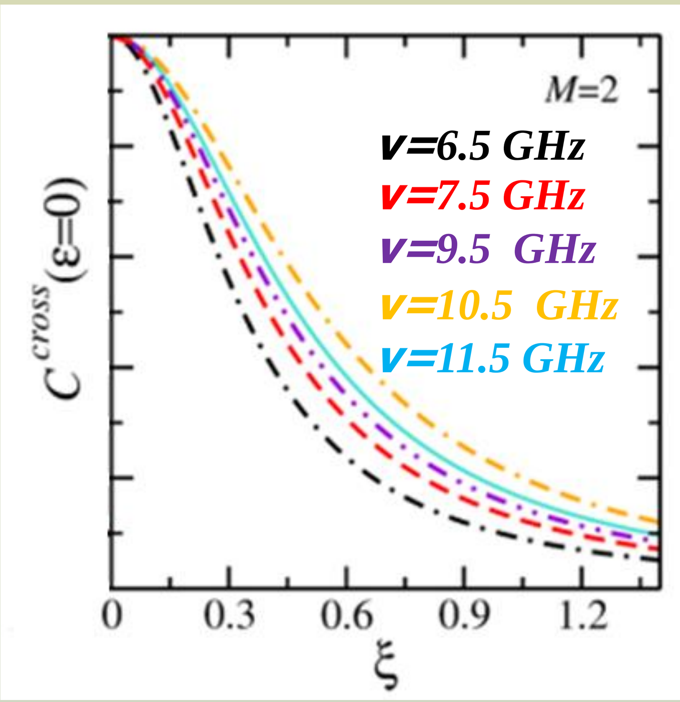


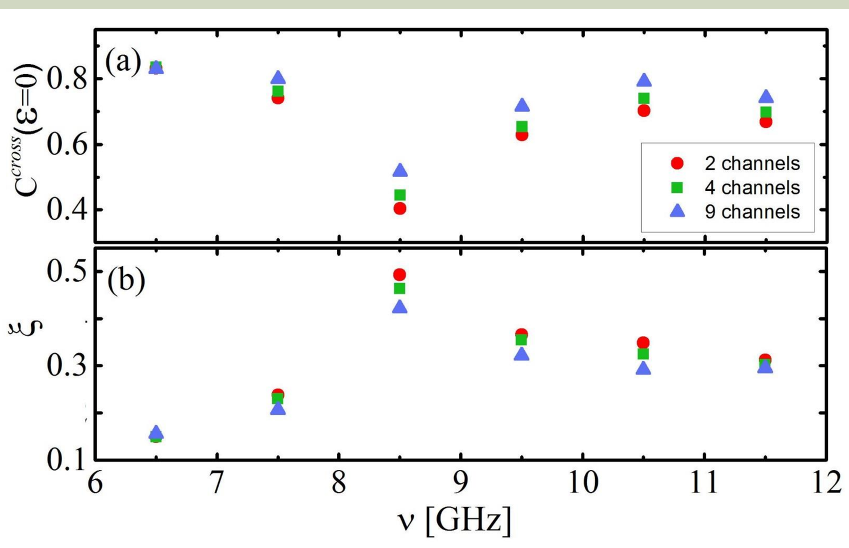
In the experiment quantum billiard is simulated by a aluminum flat microwave cavity (area A=1828.5 cm^2, height h=1.2 cm) covered by 20 µm layer of silver. Such sytem generates a chaotic dynamics since the two-dimensional Schrödinger equation for the quantum billiard is mathematically equivalent to the Helmholtz equation describing the electromagnetic field inside the cavity. The cut-off frequency of $\nu_{max}= c/2d \approx 12.49$ GHz. The homogenous magnetic field of the strength B ≈ 495 mT leads to $S_{12}(\nu) \neq S_{21}(\nu)$ of the measured two-ports scattering matrix $\hat{S}(\nu)$. The microwave antennas 1 and 2 with the length 5.8 mm were connected to the Agilent E8364B microwave network analyzer. Randomly distributed open channels $2 \leq M \leq 9$ were realized by 7 antennas shounted with 50 Ω loads. In order to create 100 realizations for the cavity a metallic perturber M_p was moved along the walls of the cavity.

THE STRENGTH OF TIV

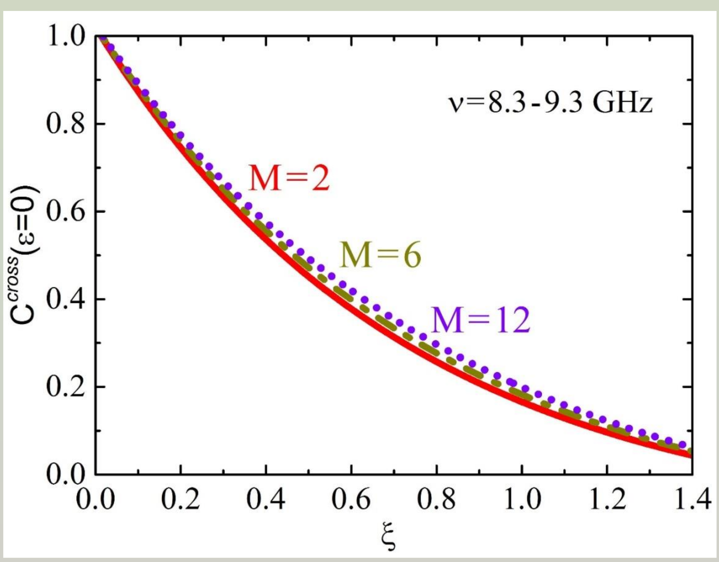
$$C_{ab}^{cross}(0) = C_{ab}^{cross}(\varepsilon = 0; \eta, \gamma, \xi) = \frac{\mathrm{Re}[\langle S_{ab}^{fl}(\nu) S_{ba}^{fl*}(\nu)\rangle]}{\sqrt{\langle |S_{ab}^{fl}(\nu)|^2\rangle \langle |S_{ba}^{fl}(\nu)|^2\rangle}}$$

The size of TIV can be quantified by using the cross- correlation coefficient $C_{ab}^{cross}(0)$. It decreases with the openness of the cavity. The distinct peak appears in the frequency interval $\nu \in [8,9]$ GHz, here TIV is the largest, $\xi \approx 0.49$.





(a) *Experimentally determined* $C_{ab}^{cross}(0)$ *over 100 cavity realizations.*
(b) The *strength* ξ *of TIV.*

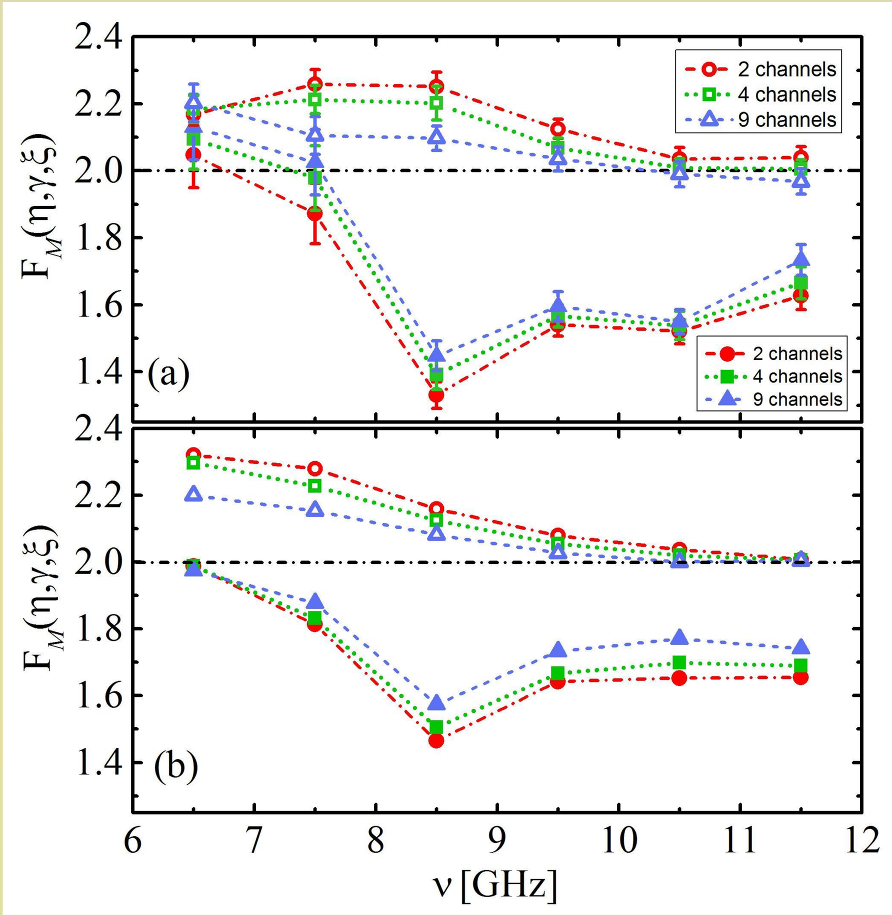


The experimental cross-correlation coefficient.

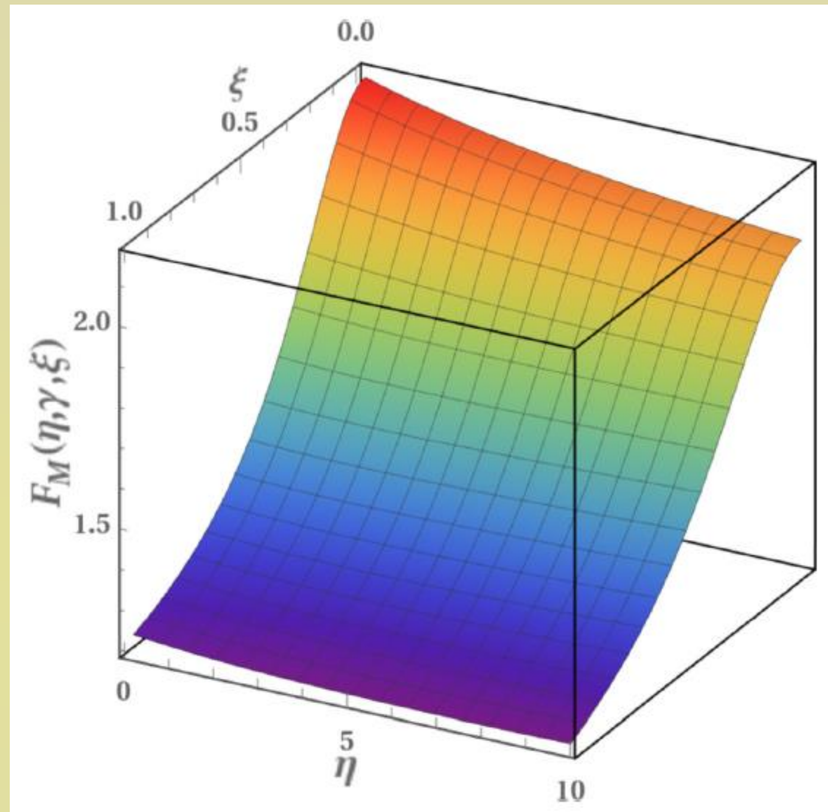
ELASTIC ENHANCEMENT FACTOR

The elastic enhancement factor $F_M(\eta, \gamma, \xi)$ as function of ξ and M can be expressed in terms of Ŝ-matrix elements $|S_{ab}^{fl}|^2 \equiv C_{ab}(0; \eta, \gamma, \xi)$

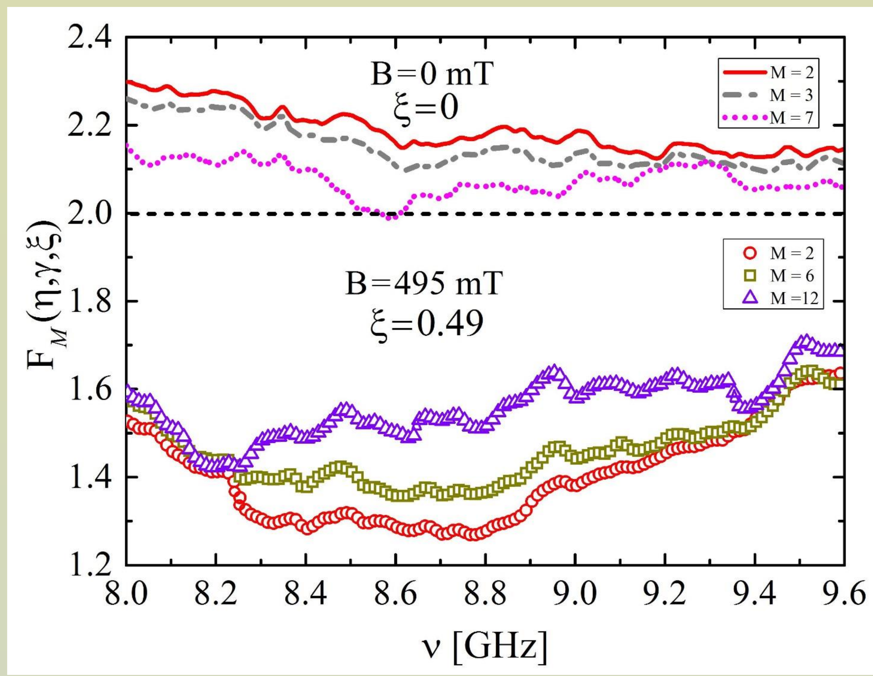
$$F_M(\eta,\gamma,\xi) = \frac{\sqrt{C_{aa}(0;\eta,\gamma,\xi) C_{bb}(0;\eta,\gamma,\xi)}}{\sqrt{C_{ab}(0;\eta,\gamma,\xi) C_{ba}(0;\eta,\gamma,\xi)}}$$



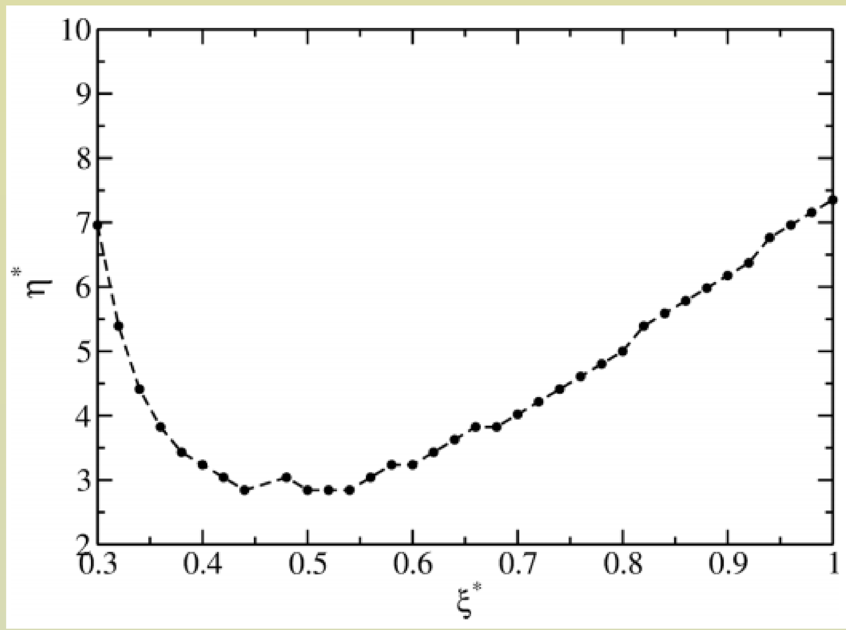
(a) *Experimental EEF with standard deviations was obtained without and with magnetized ferrite inside the cavity by averaging over 100 microwave billiard realizations (respectively empy and full symbols). The black dash-dotted line sepatare the case of preserved and violated $\mathcal{T}$-invariance.*
(b) *Same as (a) for RMT results.*



Three- dimensional plot of the computed EEF versus η for fixed M =10 open channels and γ =10 (T and ξ were varied)- results for RMT .



Experimental EEF averaged over 100 realizations of the cavity in the frequency range $\nu \in [8; 9.6]$ GHz.



Changes of EEF - extracted from 3D plot. The results are in accordance with experimental findings. The experimental values of opennes are larger than η* for ξ>0.2 hence the effect of $\mathcal{T}$-invariance violation on the EEF dominates over that of the openness.

For a fixed number M of open channels and partial TIV (when β=2), the elastic enhancement factor decreases with increazing the size of TIV induced by the magnetized ferrite. The increase of the number *M* leads to a decrease of the electric-field intensity and causes a boost of EEF. The opposite behavior of the enhancement was observed for ξ=0. The RMT results reproduce the course of the experimental ones. The strong dip in the range $\nu \in [8,9]$ GHz coincides with that of the largest TIV, for $\xi \approx 0.49$. The experimental and numerical results corroborate the crossover from GOE (for ξ=0) to GUE (for ξ=1). The measured frequency range $\nu \in [6,12]$ GHz corresponds to the Ohmic absorption strength $6 \leq \gamma \leq 15$ due to the presence of the lossy ferrites.

CONCLUSIONS The elastic enhancement factor depends on the size of $\mathcal{T}$-invariance violation. The increase of the number of open channels *M* causes a boost of the elastic enhancement factor. The experimental results are in good agreement with the theoretical predictions.

ACKNOWLEDGMENTS This work was supported in part by the National Science Centre, Poland, Grant No UMO-2018/30/Q/ST2/00324. B.D. thanks the National Natural Science Foundation of China for financial support through Grants No. 11775100, No. 11961131009, and No. 12047501. Supported by the 111 Project under Grant No. B20063.

REFERENCES

[1] M. Białous, B. Dietz, and L. Sirko, Phys. Rev. E **102**, 042206 (2020).
[2] M. Białous, B. Dietz, and L. Sirko, Acta Phys. Pol. A **139**, 462 (2021).
[3] M. Białous, B. Dietz, and L. Sirko, Phys. Rev. E **103**, 052204 (2021).