Quantum Chaotic Scattering in Microwave Billiards and Ericson Fluctuations Revisited – a Modern View on the Scientific Legacy of Theo Mayer-Kuckuk (1927-2014)

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BONN 2015

- Some personal recollections on M-K
- A primer on Ericson fluctuations
- Microwave billiards as model systems for chaotic scattering
- Some precision tests of fluctuation theory
- Fluctuations without and with time reversal symmetry breaking

Supported by DFG within SFB 634

S. Bittner, B. Dietz, T. Friedrich, M. Miski-Oglu, A. R., F. Schäfer
H. L. Harney, H. A. Weidenmüller, J. J. M. Verbaarschot + R. Bock

M-K in Heidelberg at the time (1953) of his Doctoral Thesis entitled:

“Messungen über den Zerfall von Ti^{51}, Al^{28}, Mg^{27} und Cl^{34} mit Szintillationsspektrometern”

M-K in Heidelberg at his Habilitation (1962): “Vergleich der β-Spektren von B^{12} und N^{12}”

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M-K had to learn how to operate a Tandem
(Van de Graaff accelerator)

M-K together with Wolfgang Gentner at the International Conference “Recent Progress in Nuclear Physics with Tandems” in Heidelberg (1966)

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M-K speaking with Joseph Zähringer at the MPI für Kernphysik during the celebration of Wolfgang Gentner‘s 60th birthday (1966)

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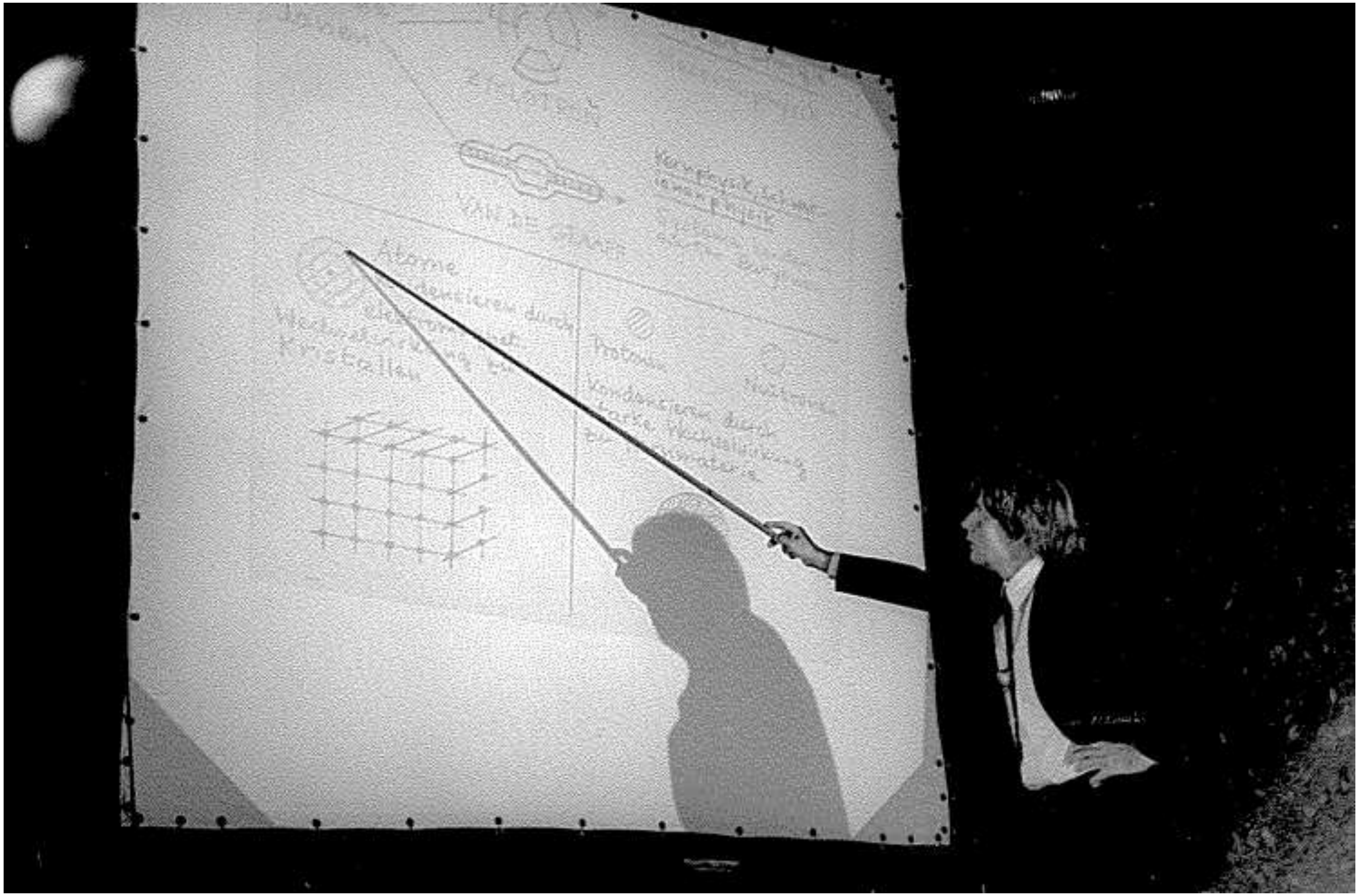
M-K at the Inauguration of VICKSI at the HMI Berlin (1979)



M-K at a Meeting of the COSY Scientific Council at the FZ Jülich (1989)

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M-K as President of the German Physical Society at the Spring Meeting of the Division "Hadrons and Nuclei" at the Technische Hochschule Darmstadt (1991)

Joint Publications with Theo Mayer-Kuckuk

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STATISTICAL FLUCTUATIONS IN THE CROSS SECTIONS OF REACTIONS $^{35}Cl(p,\alpha)^{32}S$ AND $^{37}Cl(p,\alpha)^{34}S$

P. von Brentano, J. Ernst, O. Häusser, T. Mayer-Kuckuk, A. Richter and W. von Witsch

Phys. Letters 9, (1964) 48

THE LEVEL DENSITIES IN THE COMPOUND NUCLEI ^{27}Al AND ^{38}Ar AT 20 MeV EXCITATION ENERGY

P. von Brentano, O. Häusser, T. Mayer-Kuckuk, A. Richter and W. von Witsch

Phys. Letters 14, (1965) 121

MODULATED FLUCTUATIONS IN THE REACTION $^{26}Mg(p,\alpha)\,^{23}Na$

B.W. Allardyce, P.J. Dallimore, I. Hall, N.W. Tanner, A. Richter, P. von Brentano and T. Mayer-Kuckuk

Phys. Letters 18, (1965) 140

AN ANALYSIS OF CROSS-SECTION FLUCTUATIONS IN THE REACTION $^{26}Mg(p,\alpha)^{23}Na$

B.W. Allardyce, P.J. Dallimore, I. Hall, N.W. Tanner, A. Richter, P. von Brentano and T. Mayer-Kuckuk

Nucl. Phys. 85, (1966) 193

THE STATISTICAL CHARACTER OF THE REACTION $^{37}Cl(p,\alpha)^{34}S$ AT 21-22 MeV EXCITATION ENERGY OF THE COMPOUND NUCLEUS

W. von Witsch, P. von Brentano, T. Mayer-Kuckuk and A. Richter

Nucl. Phys. 80, (1966) 394

A STATISTICAL MODEL ANALYSIS OF (p,α)-REACTIONS ON ^{26}Mg, ^{37}Cl AND ^{45}Sc

A. Richter, A. Bamberger, P. von Brentano, T. Mayer-Kuckuk and W. von Witsch

Z. Naturforsch. 21A, No.7, (1966) 1002

How It All Began…

FLUCTUATIONS OF NUCLEAR CROSS SECTIONS IN THE "CONTINUUM" REGION*

Torleif Ericson†
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received August 29, 1960; revised manuscript received October 14, 1960)

PRL **5**, 430 (1960)

A Theory of Fluctuations in Nuclear Cross Sections

TORLEIF ERICSON

CERN, Geneva, Switzerland

Ann. Phys. (N.Y.) **23**, 390 (1963)

A Primer on Ericson Fluctuations (Γ > d)

$$S_{\alpha\alpha'}(E) = i \sum_j \frac{\gamma_{\alpha j}\,\gamma_{\alpha' j}}{E - E_j + i\,\Gamma/2}$$

- $S_{\alpha\alpha'}$ are Gaussian distributed with random phases
- S-matrix correlation function

$$\langle S_{\alpha\alpha'}(E) S^*_{\alpha\alpha'}(E+\varepsilon)\rangle = \langle S_{\alpha\alpha'}(E)\, S^*_{\alpha\alpha'}(E)\,\rangle \frac{i\,\Gamma}{i\Gamma + \varepsilon}$$

- Cross section correlation function ("Autocorrelation function")

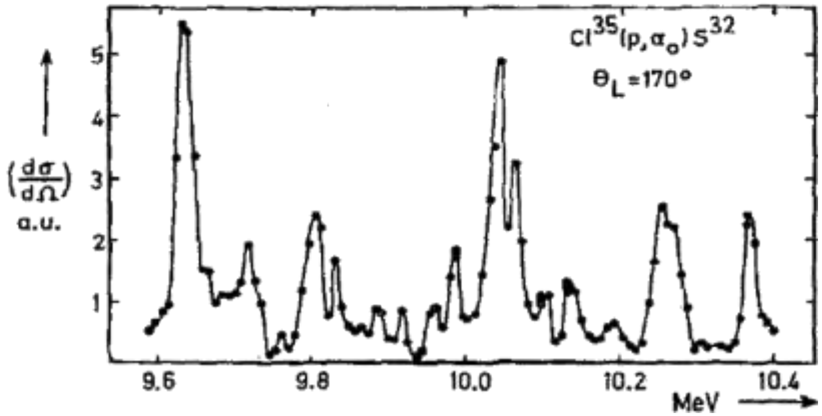
$$\langle \sigma_{\alpha\alpha'}(E)\, \sigma_{\alpha\alpha'}(E+\varepsilon)\rangle = \langle \sigma_{\alpha\alpha'}(E)\rangle^2 \left\{1 + \frac{1}{1 + (\varepsilon/\Gamma)^2}\right\}$$

behaves like a Lorentzian with a mean coherence width Γ

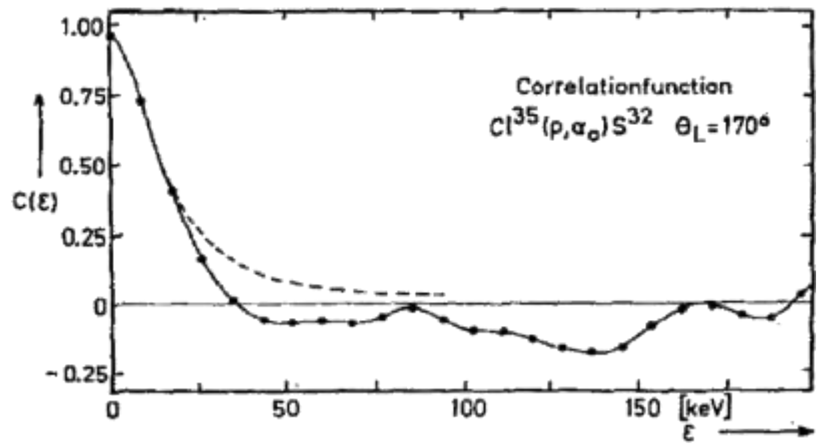
- Exponential decay of the highly excited compound nucleus

Ericson Fluctuations in Nuclear Physics

- Measured 1964 for overlapping compound nucleus resonances
  (P. v. Brentano *et al.*, Phys. Lett. **9**, (1964) 48)



- Autocorrelation function is Lorentzian



- Fluctuations also observed in other many-body quantum systems

How it All Ended for M-K: Ann. Rev. Nucl. Science **16** (1966) 183

(Times Cited: 328)

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FLUCTUATIONS IN NUCLEAR REACTIONS[1]

BY T. ERICSON
CERN, Geneva, Switzerland

AND

T. MAYER-KUCKUK
University of Bonn, Bonn, Germany

CONTENTS

Ericson Fluctuations in Other Many-Body Quantum Systems

VOLUME 60, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1988

Classical Irregular Scattering and Its Quantum-Mechanical Implications

R. Blümel and U. Smilansky

Max Planck Institute for Quantum Optics, 8046 Garching, Federal Republic of Germany, and Department of Nuclear Physics, The Weizmann Institute of Science, 76100 Rehovot, Israel

(Received 28 September 1987)

Ericson Fluctuations in Other Many-Body Quantum Systems

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ERICSON FLUCTUATIONS VERSUS CONDUCTANCE FLUCTUATIONS:

Similarities and differences

Hans A. WEIDENMÜLLER

Max-Planck-Institut für Kernphysik, Heidelberg, Fed. Rep. Germany

Nucl. Phys. A **518**, 1 (1990)

Ericson Fluctuations in Other Many-Body Quantum Systems

Nuclear Physics A518 (1990) 58–72
North-Holland

A TEST OF PARITY CONSERVATION IN THE REACTION $^{27}Al(\vec{p}, \alpha)^{24}Mg$ IN THE REGIME OF ERICSON FLUCTUATIONS*

G. BÖHM, P. VON BRENTANO, A. DEWALD, H. PAETZ GEN. SCHIECK, G. RAUPRICH, R. RECKENFELDERBÄUMER, L. SYDOW and R. WIROWSKI

Institut für Kernphysik, Universität zu Köln, D-5000 Köln, Fed. Rep. Germany

Received 5 March 1990

Ericson Fluctuations in Other Many-Body Quantum Systems

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PHYSICAL REVIEW C VOLUME 44, NUMBER 6 DECEMBER 1991

Determination of the level density of ^{29}Si from Ericson fluctuations

V. Mishra, N. Boukharouba, S. M. Grimes,* K. Doctor,† and R. S. Pedroni
Ohio University, Athens, Ohio 45701

R. C. Haight
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 11 March 1991)

Ericson Fluctuations in Other Many-Body Quantum Systems

VOLUME 69, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1992

Ericson Fluctuations in the Chaotic Ionization of the Hydrogen Atom in Crossed Magnetic and Electric Fields

Jörg Main and Günter Wunner
Theoretische Physik I, Ruhr-Universität Bochum, 4630 Bochum 1, Germany
(Received 11 February 1992)

Ericson Fluctuations in Other Many-Body Quantum Systems

PHYSICAL REVIEW C VOLUME 55, NUMBER 1 JANUARY 1997

Determination of the ^{29}Si level density from 3 to 22 MeV

F. B. Bateman,* S. M. Grimes, N. Boukharouba,† V. Mishra,‡ C. E. Brient, R. S. Pedroni,§ and T. N. Massey
Institute of Nuclear and Particle Physics, Ohio University, Athens, Ohio 45701

R. C. Haight
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 28 September 1995; revised manuscript received 2 August 1996)

Ericson Fluctuations in Other Many-Body Quantum Systems

Unimolecular Reaction of NO_2: Overlapping Resonances, Fluctuations, and the Transition State

Scott A. Reid[†] and Hanna Reisler*

Department of Chemistry, University of Southern California, Los Angeles, California 90089-0482

J. Phys. Chem. **100**, 474 (1996)

Ericson Fluctuations in Other Many-Body Quantum Systems

Giant resonance spectroscopy of ^{40}Ca with the $(e, e'x)$ reaction (III): Direct versus statistical decay ☆

J. Carter [a], H. Diesener [b,1], U. Helm [b,2], G. Herbert [b,3], P. von Neumann-Cosel [b,*], A. Richter [b], G. Schrieder [b], S. Strauch [b,4]

[a] *School of Physics, University of the Witwatersrand, PO Wits, Johannesburg, 2050 South Africa*
[b] *Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

Nucl. Phys. A **696**, 317 (2001)

Ericson Fluctuations in Other Many-Body Quantum Systems

PRL **95,** 194101 (2005) PHYSICAL REVIEW LETTERS week ending 4 NOVEMBER 2005

Quantum Chaotic Scattering in Atomic Physics: Ericson Fluctuations in Photoionization

Gernot Stania* and Herbert Walther
Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany
(Received 1 July 2005; published 1 November 2005)

Ericson Fluctuations in Other Many-Body Quantum Systems

PRL **95**, 263601 (2005) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2005

Ericson Fluctuations in an Open Deterministic Quantum System: Theory Meets Experiment

Javier Madroñero[1,2] and Andreas Buchleitner[1]

[1]*Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Str. 38, 01187 Dresden, Germany*

[2]*Physik Department, Technische Universität München, 85747 Garching, Germany*

(Received 22 September 2005; published 20 December 2005)

Ericson Fluctuations in Other Many-Body Quantum Systems

PHYSICAL REVIEW A **78**, 012701 (2008)

Signature of Ericson fluctuations in helium inelastic scattering cross sections near the double ionization threshold

Junliang Xu,[1,*] Anh-Thu Le,[1] Toru Morishita,[2] and C. D. Lin[1]
[1]*Department of Physics, Kansas State University, Manhattan, Kansas 66506, USA*
[2]*Department of Applied Physics and Chemistry, University of Electro-Communications, Tokyo, 182-8585, Japan and PRESTO, JST, Kawaguchi, Saitama, 332-0012, Japan*
(Received 26 February 2008; published 1 July 2008)

Ericson Fluctuations in Other Many-Body Quantum Systems

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Continuum shell model: From Ericson to conductance fluctuations

G.L. Celardo[1], F.M. Izrailev [2,3], S. Sorathia[2], V.G. Zelevinsky[3], G.P. Berman[4]
[1] *Physics Department, Tulane University, New Orleans, LA 70118, USA*
[2] *Instituto de Física, Universidad Autónoma de Puebla, Apartado Postal J-48, Puebla, Pue., 72570, México*
[3] *NSCL and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-1321, USA and*
[4] *Theoretical Division and CNLS, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

AIP Conf. Proc. **995**, 75 (2008)

Ericson Fluctuations in Other Many-Body Quantum Systems

REVIEWS OF MODERN PHYSICS, VOLUME 82, OCTOBER–DECEMBER 2010

Random matrices and chaos in nuclear physics: Nuclear reactions

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A. Richter†

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H. A. Weidenmüller‡

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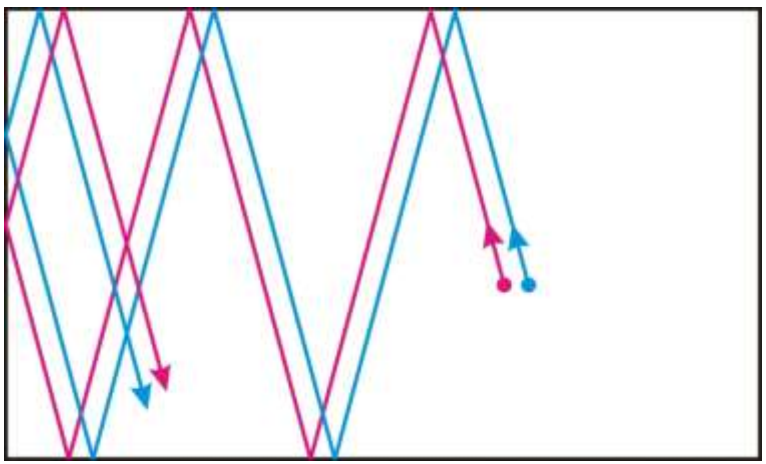
(Published 5 October 2010)

Cross Section vs. Scattering Matrix

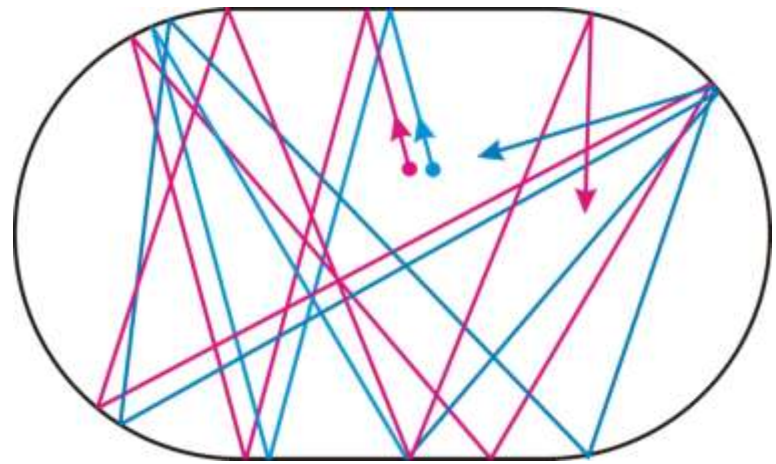
- In all studies mentioned only intensities were measured, i.e. cross sections ~ $|S|^2$
- However, an experimental acces to the scattering matrix S itself is possible in quantum billiards “constructed” from microwave resonators
- Next: something on classical and quantum billiards

Regular and Chaotic Dynamics in Classical Billiards

Rectangle (regular)



Bunimovich stadium (chaotic)



- Energy and p_x^2 are conserved
- Equations of motion are integrable
- Predictable for infinite long times

- Only energy is conserved
- Equations of motion not integrable
- Predictable for a finite time only

Small Changes → Large Actions

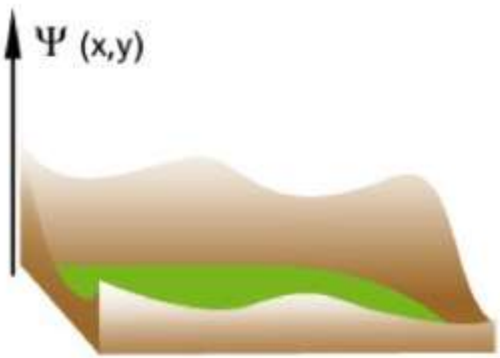
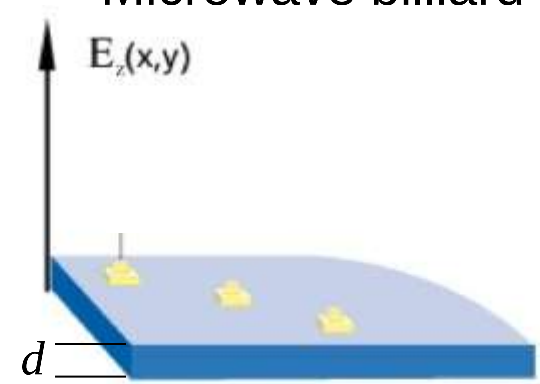
- Sensitivity of the solutions of a deterministic problem with respect to small changes in the initial conditions is called Deterministic Chaos.

- Beyond a fixed, for the system characteristic time every prediction becomes impossible. The system behaves in such a way as if not determined by physical laws but randomness.

Our Main Interest

- How are these properties of classical systems transformed into corresponding quantum-mechanical systems?
- Note: In QM distinction between integrable and chaotic systems does not work any longer:
  - Because of $\Delta x \, \Delta p \geq \hbar / 2$ the concept of trajectories loses significance
  - Schrödinger equation is linear $\rightarrow$ no chaos possible
- But: correspondence principle demands a relation between classical chaotic mechanics and quantum mechanics
  $\rightarrow$ Quantum Chaos?
- What might we learn from generic features of billiards, microscopic and mesoscopic systems (hadrons, nuclei, atoms, molecules, metal clusters, quantum dots) ?
- Quantum chaotic scattering

Quantum Billiards and Microwave Billiards

Quantum billiard	Microwave billiard
	

Analogy $\lambda > 2d$

$$\left(\frac{\hbar^2}{2m}\Delta + E\right)\Psi = 0,\ \Psi|_{\partial\Omega} = 0 \quad \longleftrightarrow \quad \left(\Delta + k^2\right)E_z = 0,\ E_z|_{\partial\Omega} = 0$$

eigenvalue E ↔ wave number $k = \frac{2\pi f}{c}$

eigenfunction Ψ ↔ electric field strength E_z

- Recently we made further steps towards an experimental realization of **Quantum Dirac Billiards** to study relativistic effects through **Microwave Billiards modelling Graphen**

Microwave Resonator as a Model for the Compound Nucleus

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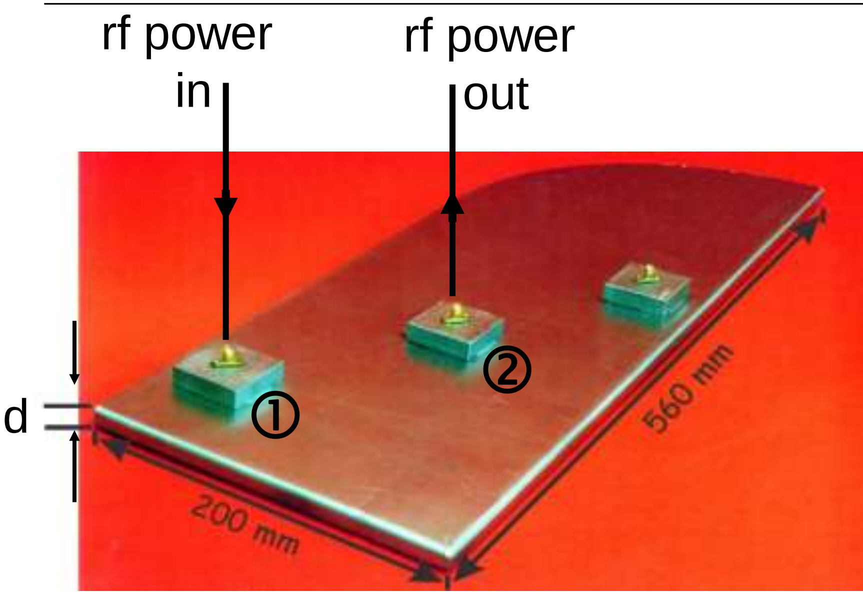

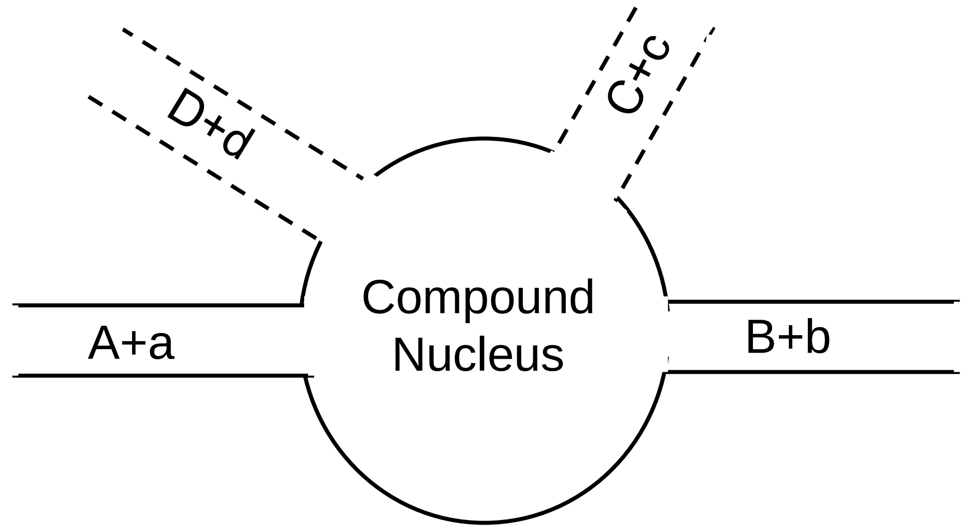

- Microwave power is **emitted** into the resonator by antenna ① and the output signal is **received** by antenna ② → **Open scattering system**
- The antennas act as **single scattering channels**
- Absorption at the walls is modeled by **additive channels**
- Manufactured at CERN from surplus Nb metal sheets of sc LEP cavities

Superconducting **DA**rmstadt Electron **LIN**ear **Ac**celerator (**S-DALINAC**)

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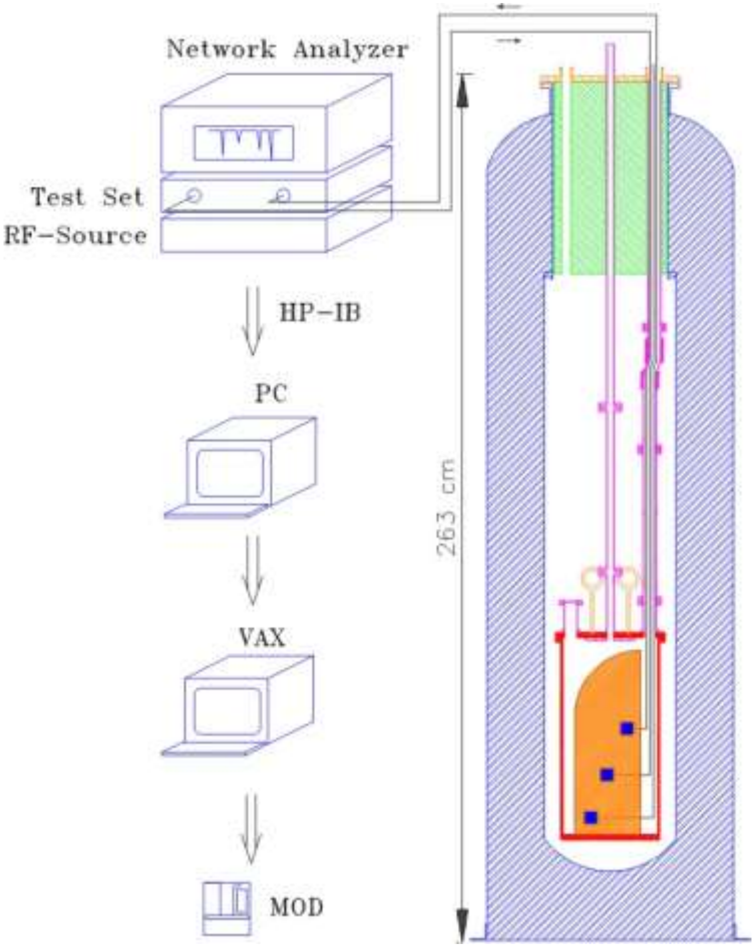
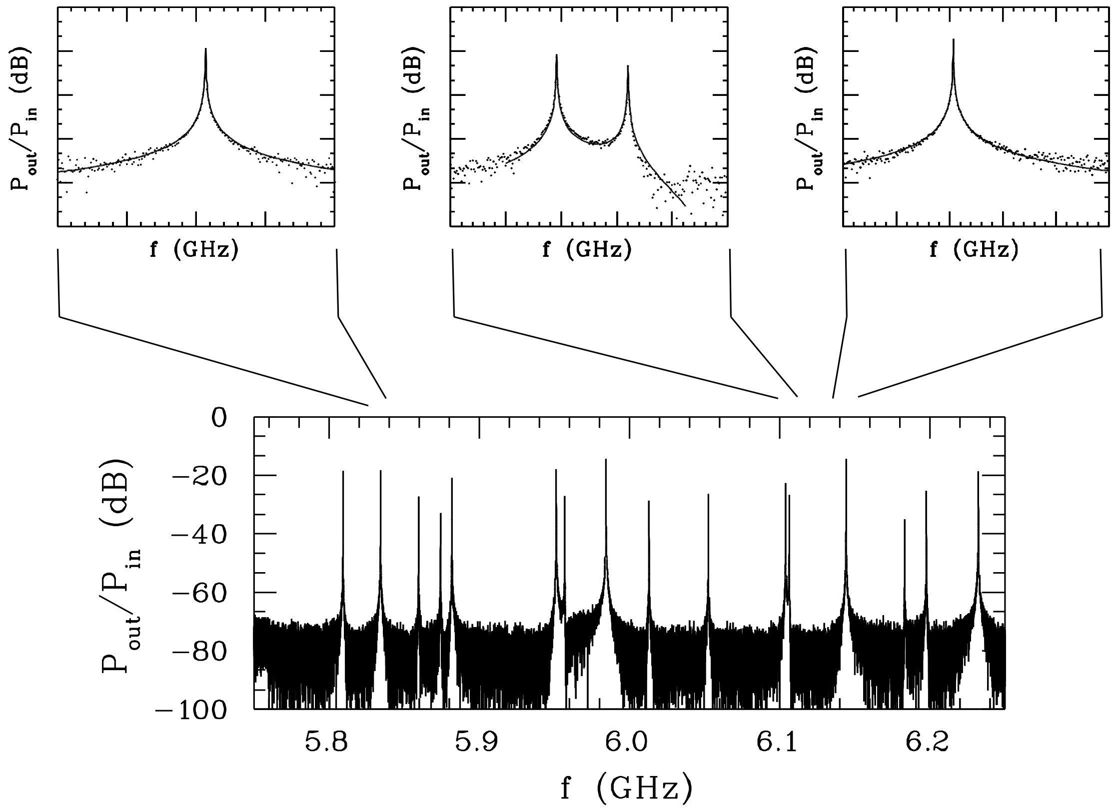
Experimental Setup



- Superconducting cavities
- LHe (T = 4.2 K)
- f = 45 MHz ... 50 GHz
- $10^3 \ldots 10^4$ eigenfrequencies
- $Q = f/\Delta f \approx 10^6$

Typical Transmission Spectrum

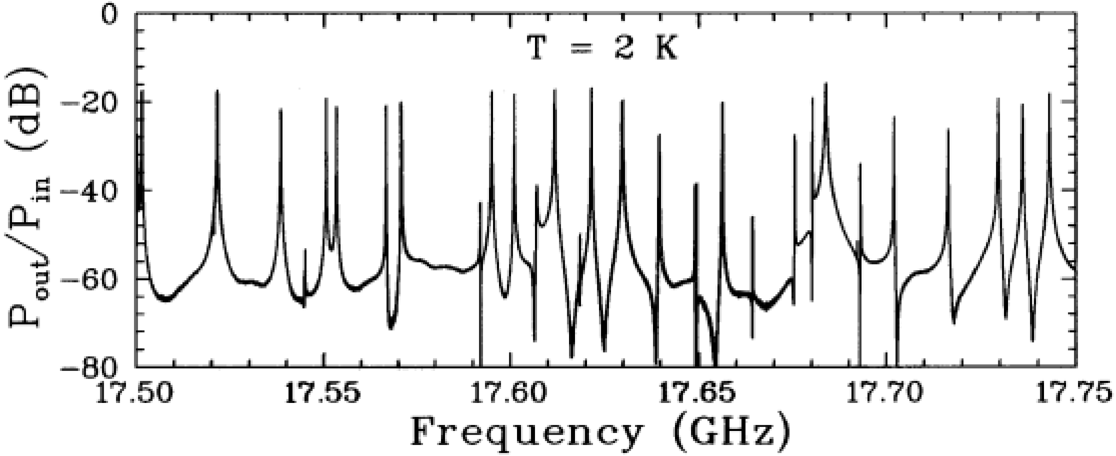


- Transmission measurements: relative power from antenna a → b

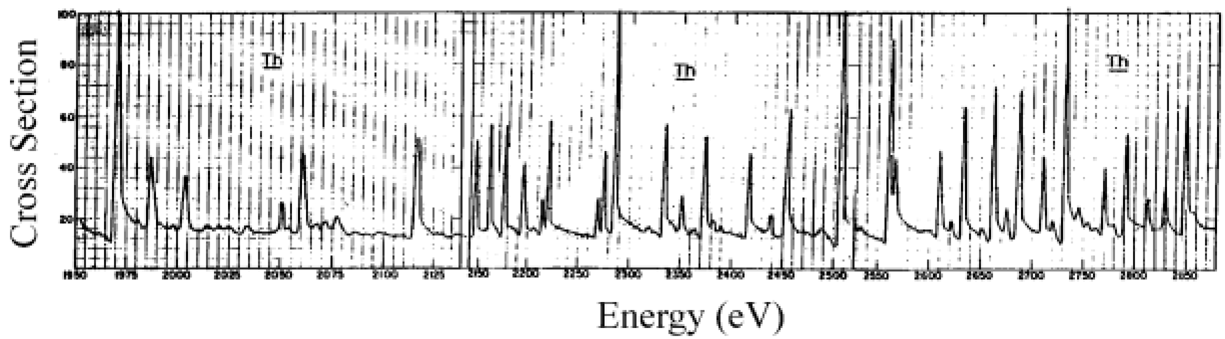
$$P_{out,b} / P_{in,a} = |S_{ba}|^2$$

Stadium Billiard ↔ n + ^{232}Th

Transmission spectrum for the stadium billiard



Spectrum of neutron resonances in ^{232}Th + n



- Universal (generic) behavior of the two chaotic systems

Scattering Matrix Description within the "Heidelberg Approach"

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- $$S(E) = 1 - 2\pi i\, W (E - H + i\pi\, W^{\dagger} W)^{-1} W^{\dagger}$$

Nucleus		**Microwave billiard**
energy E	$\leftarrow E, f \rightarrow$	frequency f
nuclear Hamiltonian	$\leftarrow H \rightarrow$	resonator Hamiltonian
coupling of quasi-bound states to channel states	$\leftarrow W \rightarrow$	coupling of resonator states to antenna states and to absorptive channels

- Experiment measures complex S-matrix elements
- **RMT description**: replace H by a GOE / GUE matrix for T-inv / T-noninv systems

Resonance Parameters

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- Use eigenrepresentation of

$$H_{eff} = H - i\,\pi W^{\dagger} W$$

and obtain for a scattering system with isolated resonances

a → resonator → b

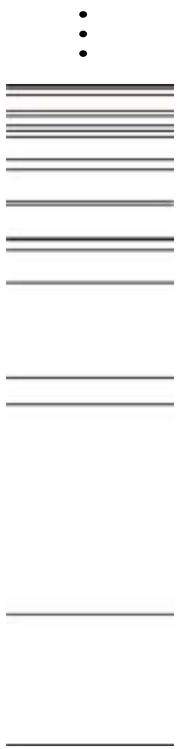
$$S_{ba} = \delta_{ba} - i \sum_{\mu} \frac{\sqrt{\Gamma_{\mu a} \Gamma_{\mu b}}}{f - f_{\mu} + (i/2)\Gamma_{\mu}}$$

- Here: f_{μ} = real part, Γ_{μ} = imaginary part } of eigenvalues of H_{eff}

- Partial widths $\Gamma_{\mu a}$, $\Gamma_{\mu b}$ fluctuate and total widths Γ_{μ} also

Excitation Spectra

atomic nucleus



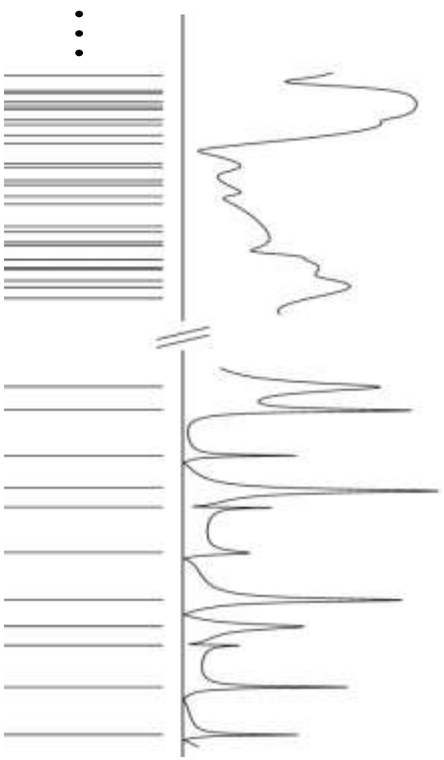
$\rho \sim \exp(E^{1/2})$

overlapping resonances
for Γ/d > 1
Ericson fluctuations

weakly overlapping
resonances for Γ/d ≲ 1

isolated resonances
for Γ/d << 1

microwave cavity

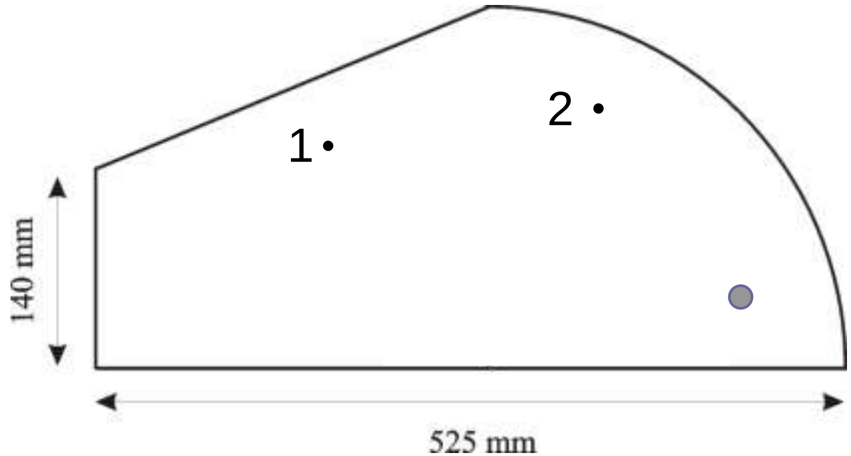


$\rho \sim f$

- Universal description of spectra and fluctuations:
  Verbaarschot, Weidenmüller and Zirnbauer (1984)

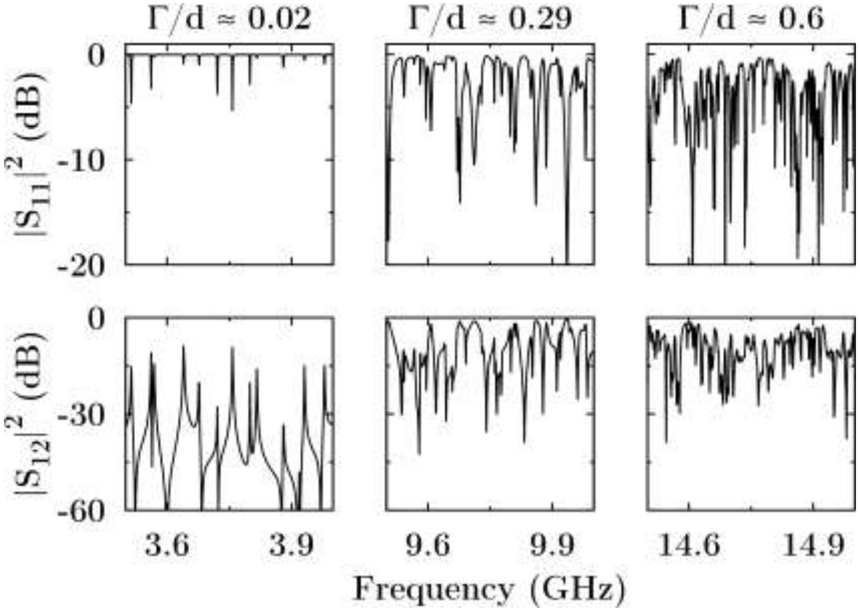
Fully Chaotic Microwave Billiard

- Tilted stadium (Primack+Smilansky, 1994)



- Only vertical TM_0 mode is excited in resonator → simulates a quantum billiard with dissipation
- Additional scatterer → improves statistical significance of the data sample
- Measure complex S-matrix for two antennas 1 and 2: S_{11}, S_{22}, S_{12}, S_{21}

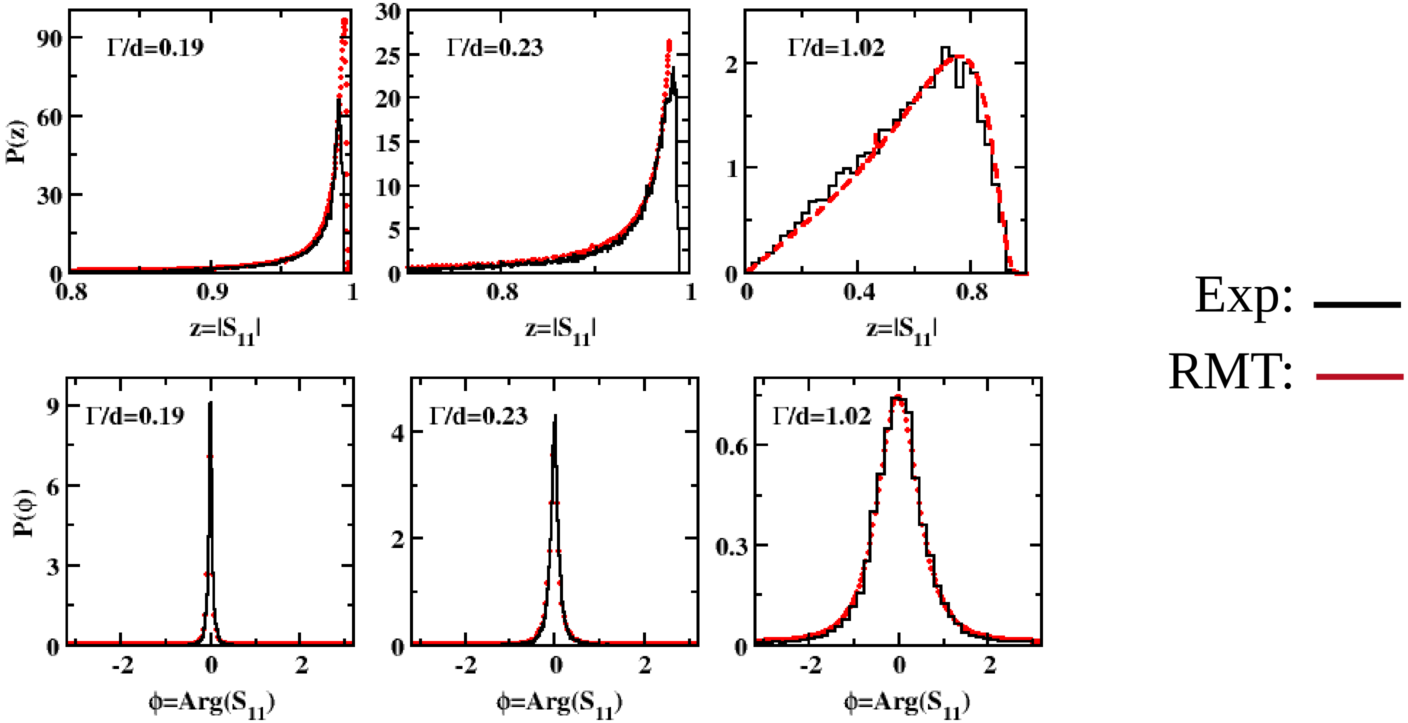
Spectra and Correlations of S-Matrix Elements



- Γ/d <<1: isolated resonances → eigenvalues, partial and total widths
- Γ/d ≲ 1: weakly overlapping resonances and strongly overlapping resonances (Γ/d >1) → investigate S-matrix fluctuation properties with the autocorrelation function and its Fourier transform

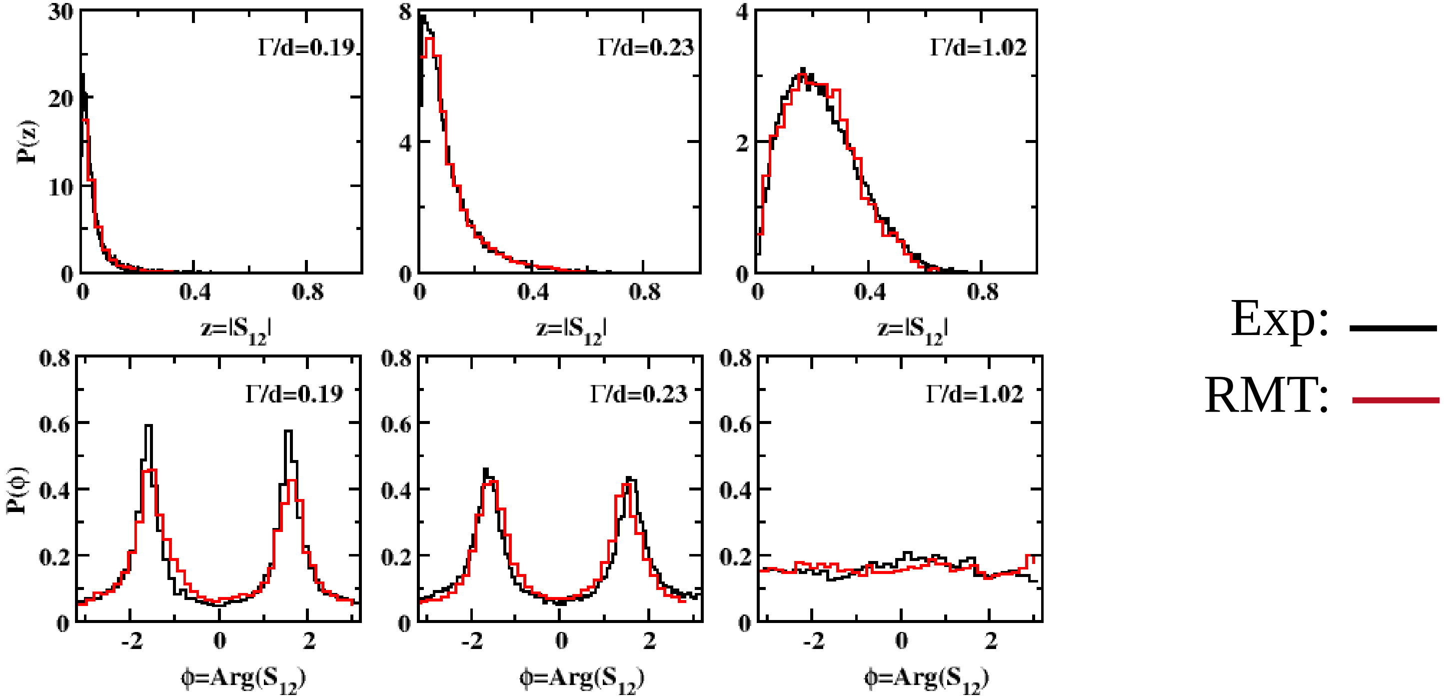
$$C_{ab}(\varepsilon) = \left\langle S_{ab}(f) S^*_{ab}(f+\varepsilon) \right\rangle - \left\langle S_{ab}(f) \right\rangle \left\langle S^*_{ab}(f+\varepsilon) \right\rangle$$

Experimental Distribution of S_{11} and Comparison with RMT Predictions of Fyodorov, Savin and Sommers (2005)



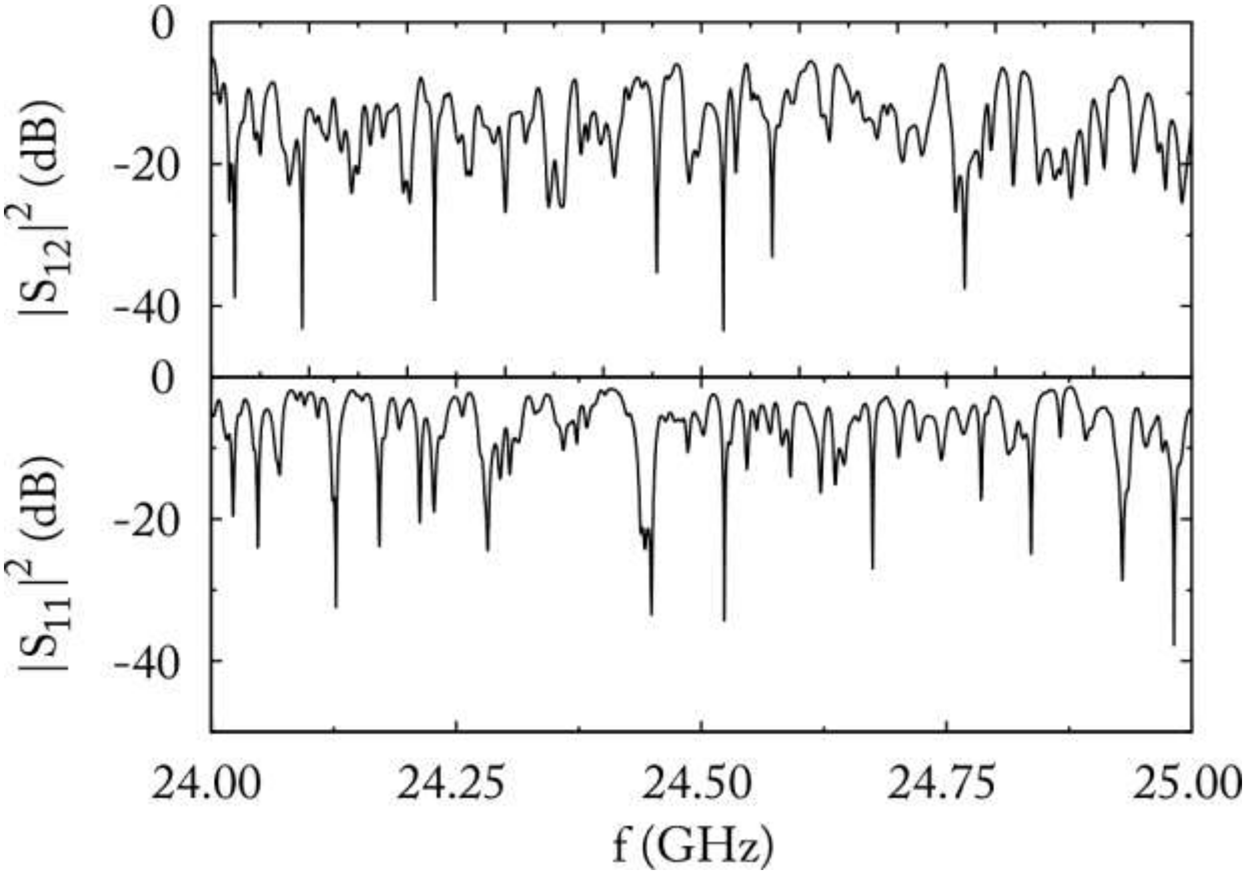
- Distributions of modulus **z** are not bivariate Gaussians
- Distributions of phases ϕ are not uniform

Experimental Distribution of S_{12} and Comparison with RMT Simulations

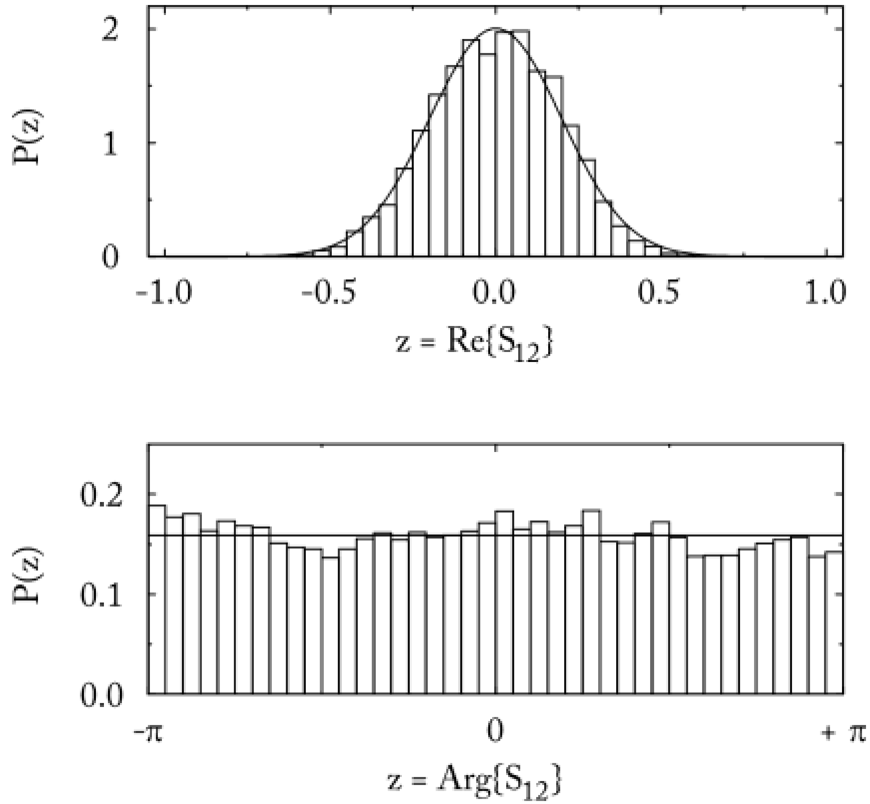


- For Γ/d =1.02 the distribution of S_{12} is close to Gaussian and the phases become uniformly distributed → Ericson regime
- Recent analytical results agree with data

Measured Fluctuations in the Ericson Regime

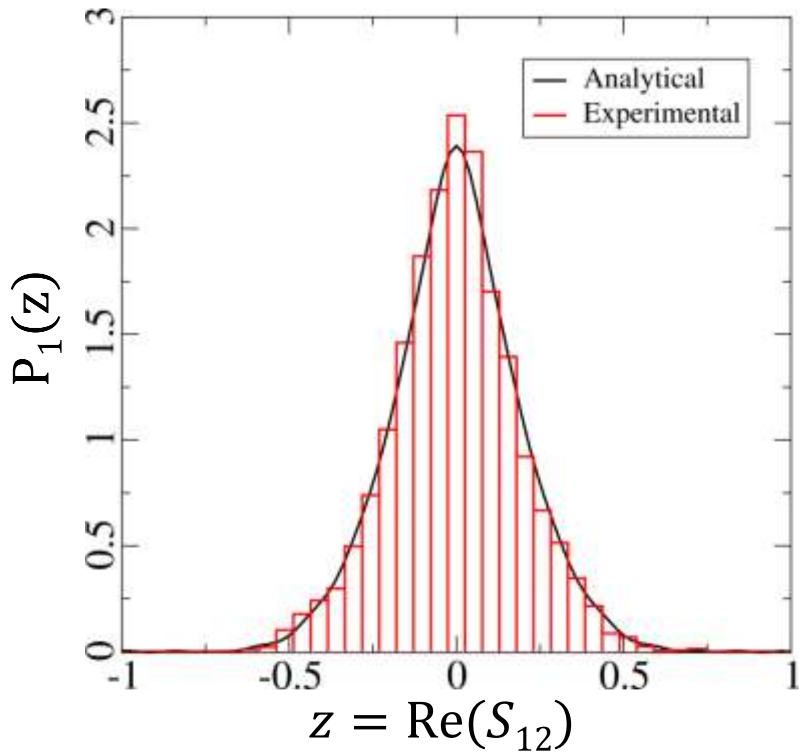


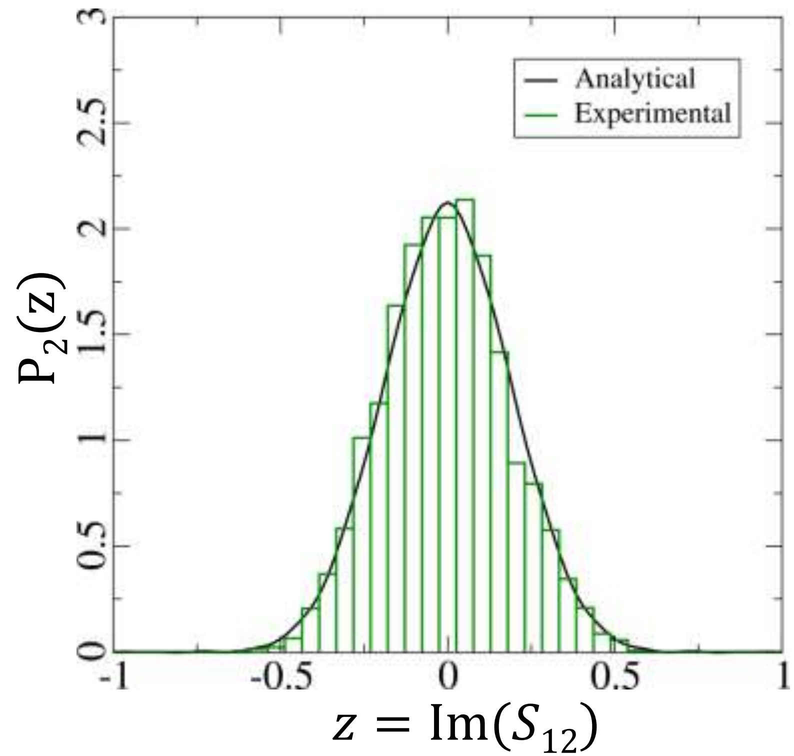
Distributions of S-Matrix Elements in the Ericson Regime



- Experiment confirms Ericson's original assumption of Gaussian distributed S-matrix elements with random phases

Experimental Distribution of S_{12} and Comparison with Predictions of Guhr, Kumar, Nock and Sommers (2013)





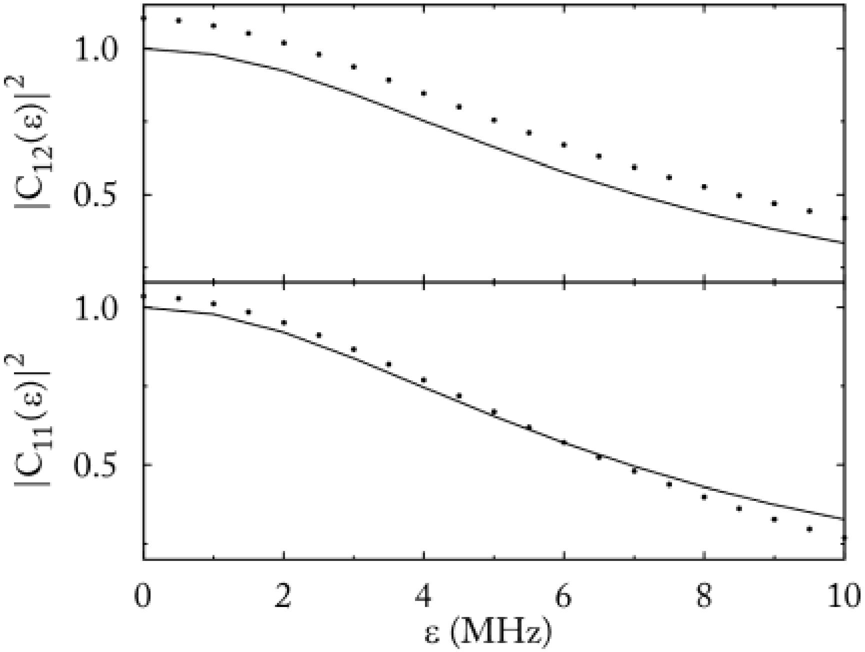
- Frequency range between 24 and 25 GHz (Γ/d =1.21)
- Published in Phys. Rev. Lett. **111**, 030403 (2013)

Road to Analysis of the Measured Fluctuations

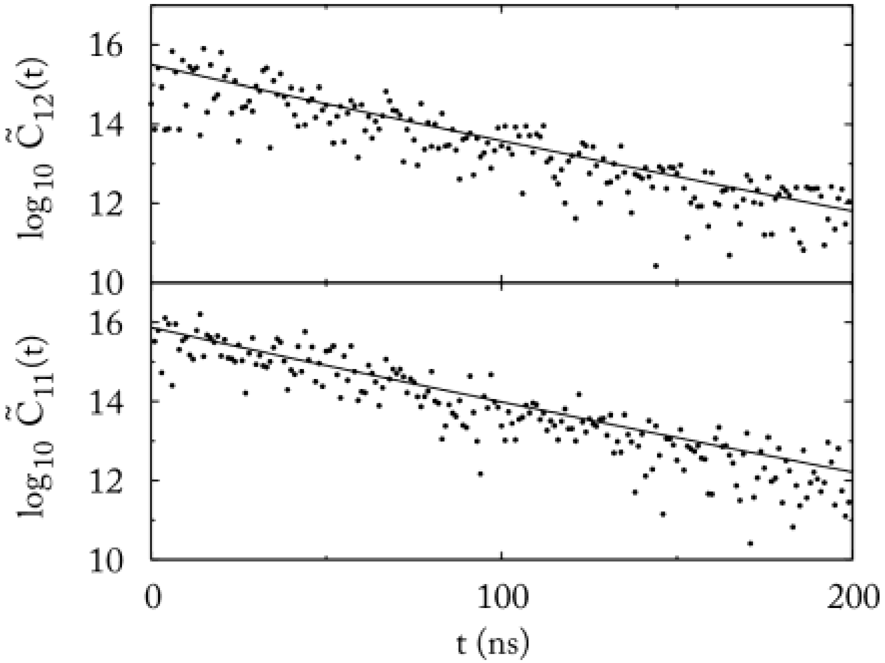
- Problem: adjacent points in $C(\varepsilon)$ correlated
- Solution: FT of $C(\varepsilon) \rightarrow$ uncorrelated Fourier coefficients $\tilde{C}(t)$
  Ericson (1965)
- Development of non-Gaussian fit and test procedure

Autocorrelation Function and Fourier Coefficients in the Ericson Regime

Frequency domain



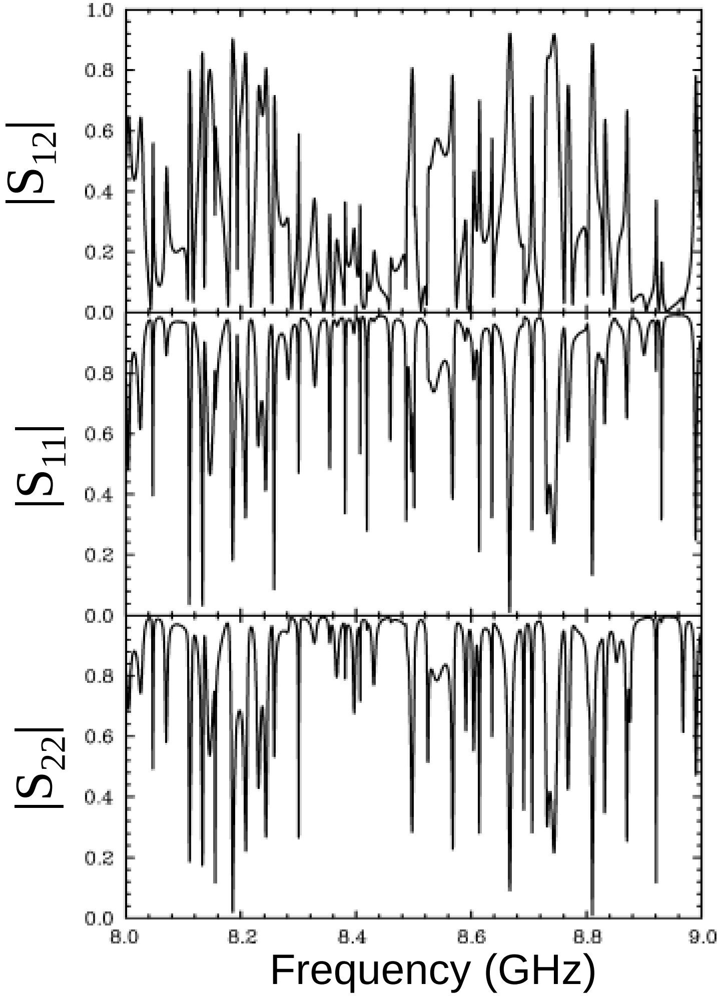
Time domain



- $|C(\varepsilon)|^2$ is of Lorentzian shape → exponential decay

Spectra of S-Matrix Elements in the Regime $\Gamma/d \lesssim 1$

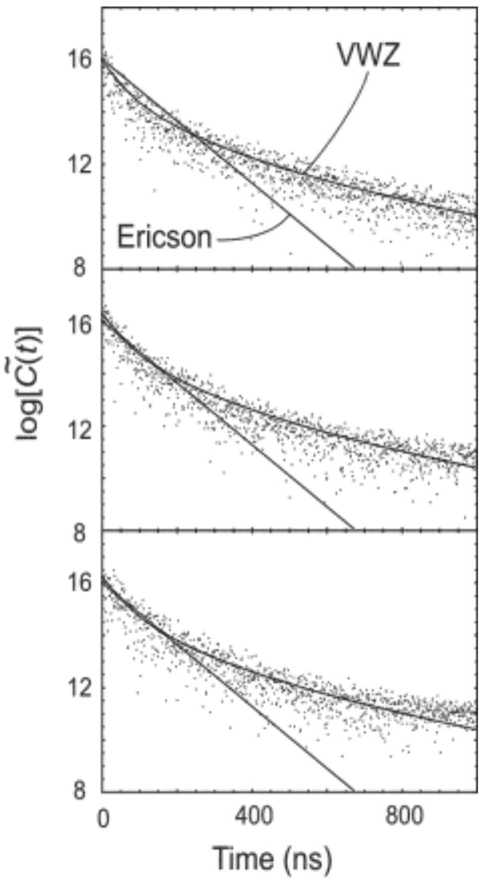
Example: 8-9 GHz



How does the system decay?

Fourier Transform vs. Autocorrelation Function

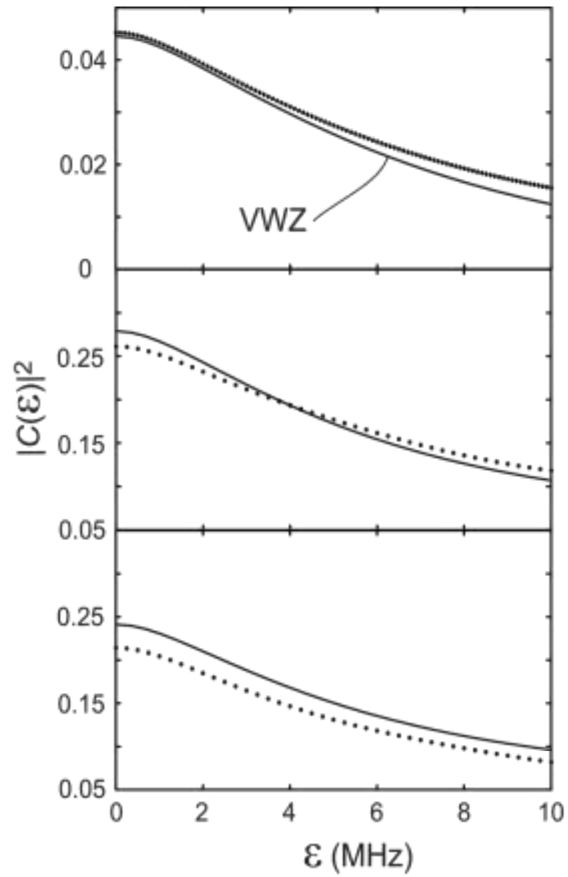
Time domain | Example 8-9 GHz | Frequency domain



$\leftarrow S_{12} \rightarrow$

$\leftarrow S_{11} \rightarrow$

$\leftarrow S_{22} \rightarrow$



Exact RMT Result for GOE Systems

TECHNISCHE UNIVERSITÄT DARMSTADT

- Verbaarschot, Weidenmüller and Zirnbauer (VWZ) 1984 for arbitrary Γ/d

- VWZ-Integral

$$C = C(T_i, \mathrm{d}\,;\,\varepsilon)$$

$$C_{ab}(\epsilon) = \frac{1}{8}\int_0^\infty d\lambda_1 \int_0^\infty d\lambda_2 \int_0^1 d\lambda\, \mu(\lambda,\lambda_1,\lambda_2) \times \exp\left(-i\pi\epsilon(\lambda_1+\lambda_2+2\lambda)/D\right) \times J_{ab}(\lambda,\lambda_1,\lambda_2) \times \prod_c \frac{(1-T_c\lambda)}{((1+T_c\lambda_1)(1+T_c\lambda_2))^{1/2}}$$

$$\mu(\lambda,\lambda_1,\lambda_2) = \frac{\lambda(1-\lambda)|\lambda_1-\lambda_2|}{(\lambda+\lambda_1)^2(\lambda+\lambda_2)^2(\lambda_1\lambda_2(1+\lambda_1)(1+\lambda_2))^{1/2}}$$

$$J_{ab}(\lambda,\lambda_1,\lambda_2) = \delta_{ab}\,T_a^2\,(1-T_a)\times\left(\frac{\lambda_1}{1+T_a\lambda_1}+\frac{\lambda_2}{1+T_a\lambda_2}+\frac{2\lambda}{1-T_a\lambda}\right) + (1+\delta_{ab})\,T_a\,T_b \times\left(\frac{\lambda_1(1+\lambda_1)}{(1+T_a\lambda_1)(1+T_b\lambda_1)}+\frac{\lambda_2(1+\lambda_2)}{(1+T_a\lambda_2)(1+T_b\lambda_2)}+\frac{2\lambda(1-\lambda)}{(1-T_a\lambda)(1-T_b\lambda)}\right)$$

- Rigorous test of VWZ: isolated resonances, i.e. $\Gamma \ll \mathrm{d}$

- First test of VWZ in the intermediate regime, i.e. $\Gamma/\mathrm{d} \approx 1$, with high statistical significance only achievable with microwave billiards

- Published in Phys. Rev. E**81**, 036205 (2010)

Corollary

- Present work:
  $\mathcal{S}$-matrix → Fourier transform → decay time (indirectly measured)

- Future work at short-pulse high-power laser facilities:
  Direct measurement of the decay time of an excited nucleus might become possible by exciting all nuclear resonances (or a subset of them) simultaneously by a short laser pulse.

Search for Time Reversal Symmetry Breaking in Nuclei: Ericson Regime

TECHNISCHE UNIVERSITÄT DARMSTADT

- T. Ericson, *Nuclear enhancement of T violation effects*, Phys. Lett. **23**, 97 (1966)

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Improved Experimental Test of Detailed Balance and Time Reversibility in the Reactions $^{27}Al + p \leftrightarrows {}^{24}Mg + \alpha$

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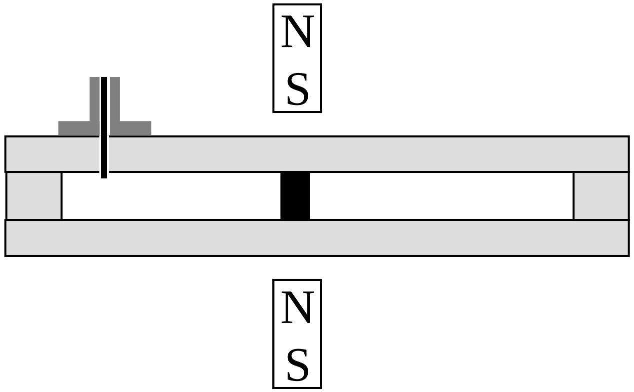
(Received 25 April 1983)

A new test of the principle of detailed balance in the nuclear reactions $^{27}Al(p,\alpha_0)^{24}Mg$ and $^{24}Mg(\alpha,p_0)^{27}Al$ at bombarding energies 7.3 MeV $\leq E_p \leq$ 7.7 MeV and 10.1 MeV $\leq E_\alpha \leq$ 10.5 MeV, respectively, is reported. Measured relative differential cross sections agree within the experimental uncertainty $\Delta = \pm 0.51\%$ and hence are consistent with time-reversal invariance. From this result an upper limit $\xi \leq 5 \times 10^{-4}$ (80% confidence) is derived for a possible time-reversal–noninvariant amplitude in the reaction.

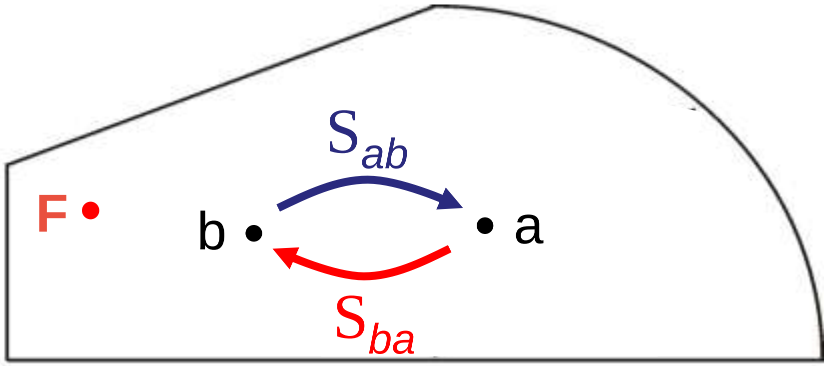
Microwave Billiard for the Study of Induced T Violation



- A cylindrical ferrite is placed in the resonator
- An external magnetic field is applied perpendicular to the billiard plane
- The strength of the magnetic field is varied by changing the distance between the magnets

Induced Violation of T-Invariance with Ferrite

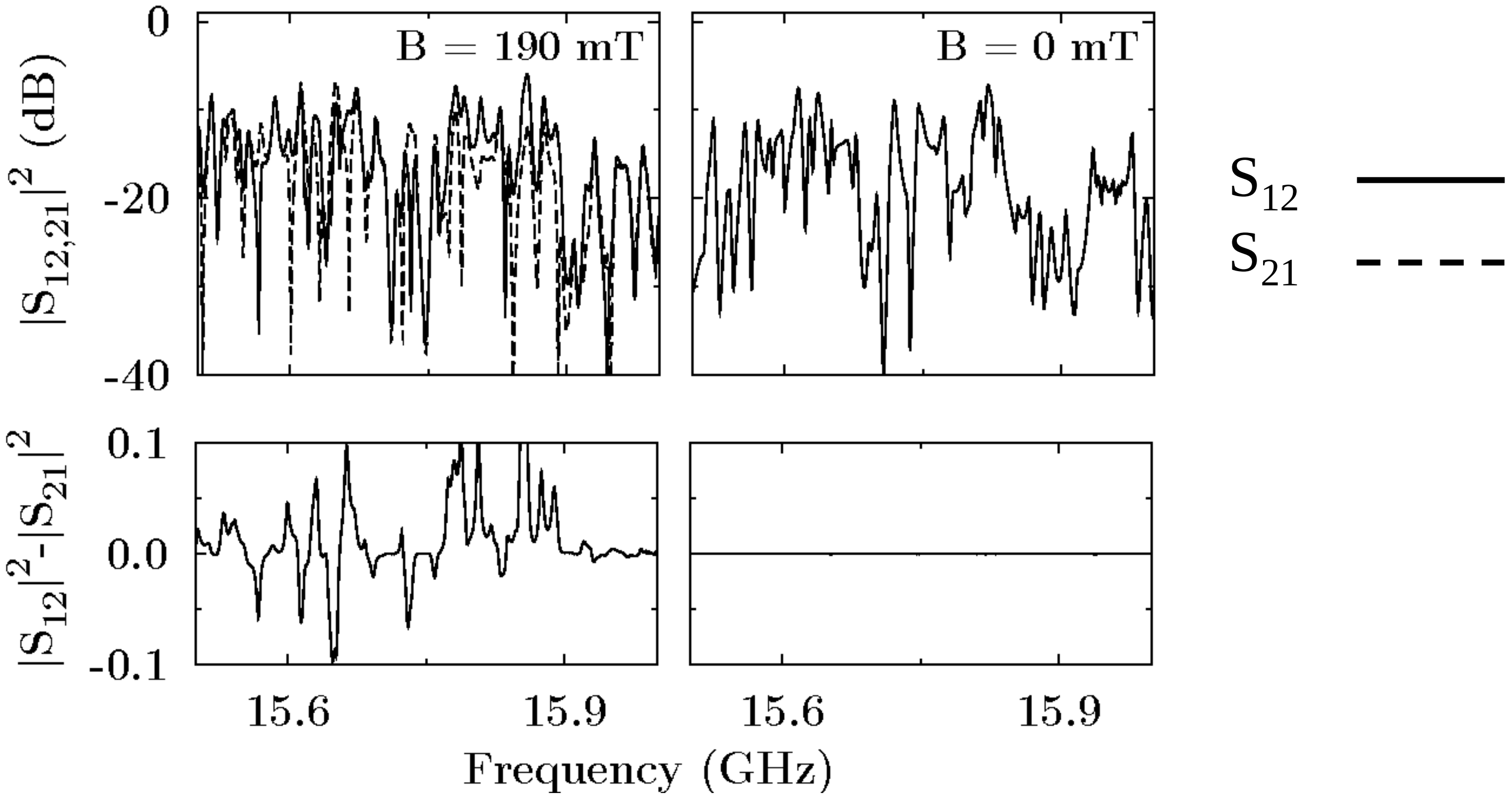
- Spins of magnetized ferrite precess collectively with their Larmor frequency about the external magnetic field
- Coupling of rf magnetic field inside resonator to the ferromagnetic resonance depends on the direction a ⇆ b



- T-invariant system → principle of reciprocity $S_{ab} = S_{ba}$

  → detailed balance $|S_{ab}|^2 = |S_{ba}|^2$

Detailed Balance in the Microwave Billiard



• Clear violation of principle of detailed balance for nonzero magnetic field B

→ How can we determine the strength of T-violation?

Analysis of T-Violation with a Crosscorrelation Function

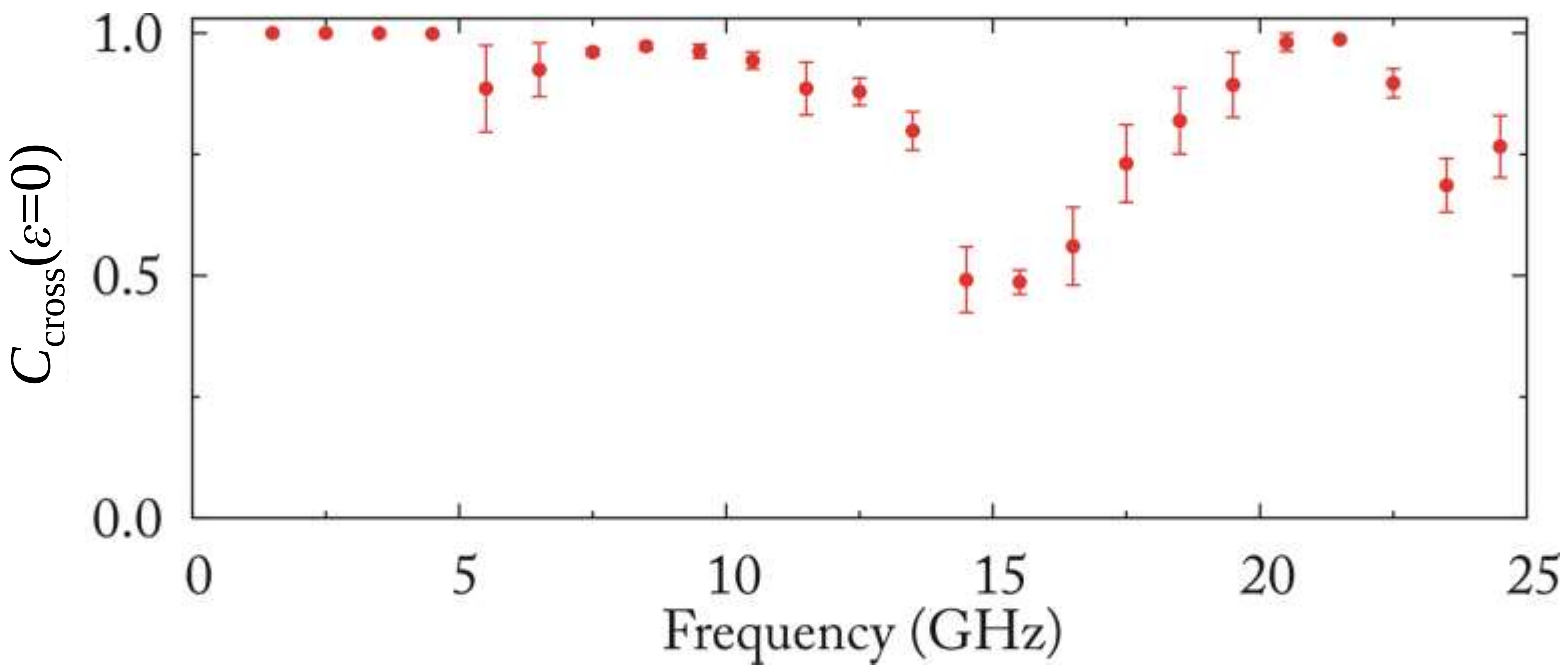
- Crosscorrelation function

$$C_{cross}(\varepsilon) = \frac{\mathrm{Re}\left(\left\langle S_{12}(f) S_{21}^{*}(f+\varepsilon) \right\rangle\right)}{\sqrt{\left\langle \left|S_{12}(f)\right|^2 \right\rangle \left\langle \left|S_{21}(f+\varepsilon)\right|^2 \right\rangle}}$$

- Special interest in crosscorrelation coefficient $C_{cross}(\varepsilon = 0)$

$$C_{cross}(\varepsilon = 0) = \begin{cases} 1 & \text{if T-invariance holds} \\ 0 & \text{if T-invariance is violated} \end{cases}$$

Experimental Crosscorrelation Coefficients



- To avoid secular variations $C_{cross}(\varepsilon=0)$ was determined in 1 GHz windows
- Around 15 GHz the effect of T-invariance violation is strongest
- $C_{cross}(\varepsilon=0) \gtrsim 0.5$: partial T-violation → mixed GOE/GUE system

RMT Result for Correlation Function with Partial T-Violation
(Phys. Rev. Lett. **103**, 064101 (2009))

- RMT analysis based on Pluhař, Weidenmüller, Zuk, Lewenkopf and Wegner (1995)

mean resonance spacing
→ from Weyl‘s formula

$$C^{(2)}_{ab}(\epsilon) = \frac{T_a T_b}{16}\int_0^\infty d\mu_1 \int_0^\infty d\mu_2 \int_0^1 d\mu \frac{|\mu_1-\mu_2|}{\mathcal{U}} \times \frac{1}{(\mu+\mu_1)^2}\frac{1}{(\mu+\mu_2)^2}\exp(\ldots) \times J_{ab}\cdot\prod_c \frac{1-T_c\mu}{\sqrt{(1+T_c\mu_1)(1+T_c\mu_2)}}\exp(-2\mathrm{t}\mathcal{H})$$

$$C^{(2)}_{ab}(T_1, T_2, \tau_{abs}; d, \varepsilon, \xi)$$

$$T_c = 1 - \left|\overline{S}_{cc}\right|^2$$

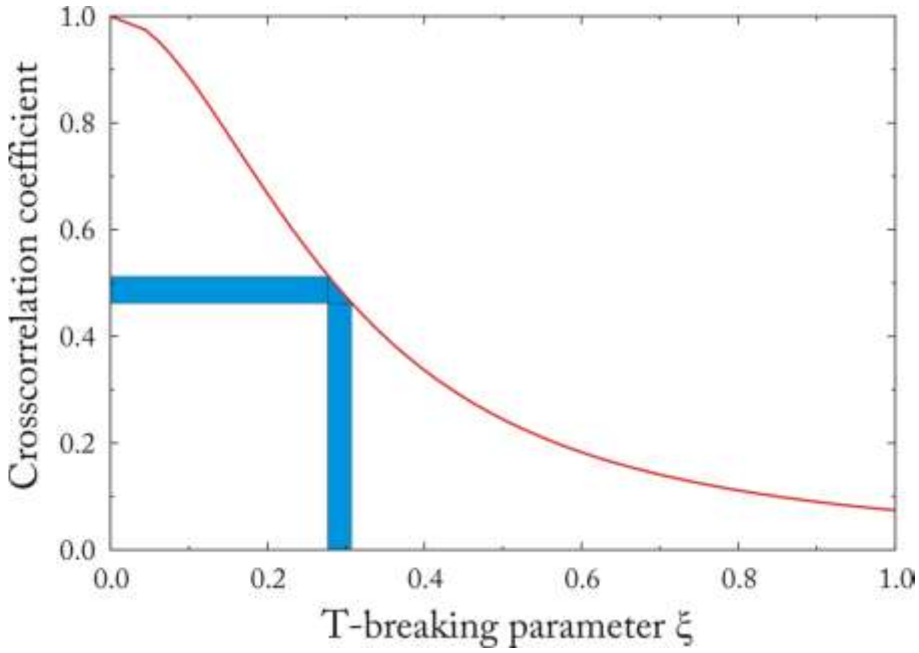
$$\tau_{abs} = \sum_{\text{absorptive channels}} T_a$$

parameter for strength of T-violation
→ from crosscorrelation coefficient

transmission coefficients
→ from autocorrelation function

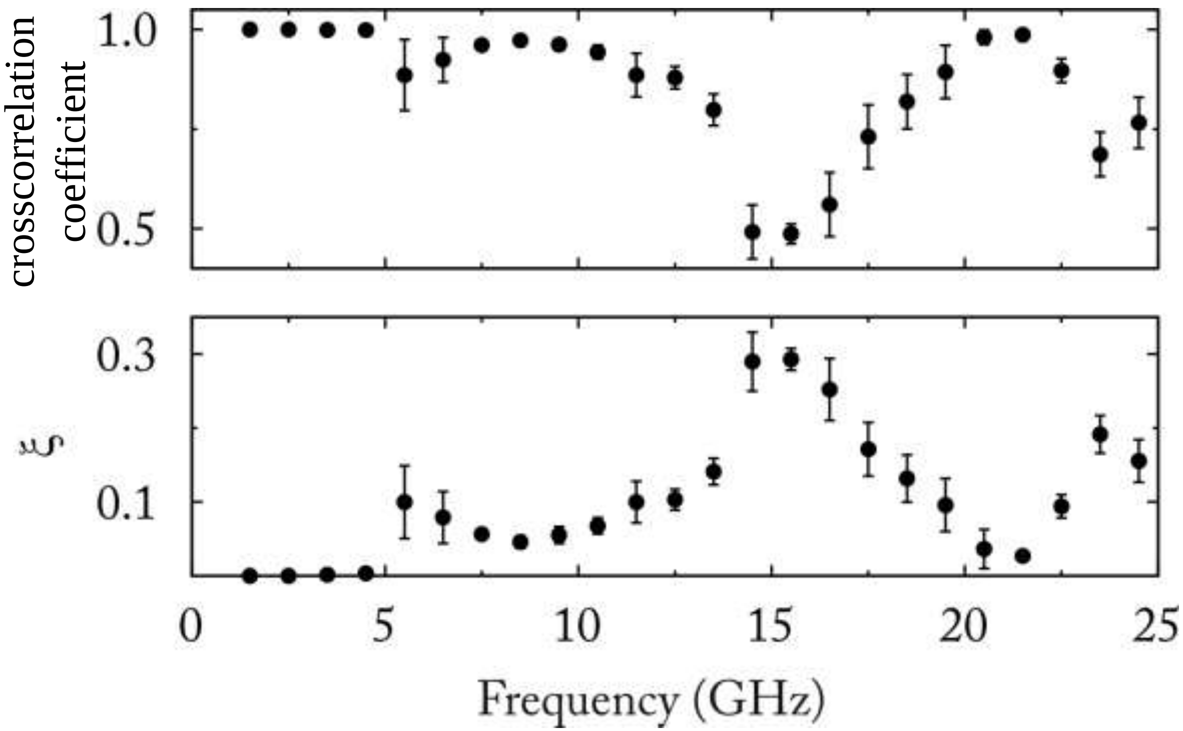
Exact RMT Result for Partial T-Breaking

- RMT analysis based on Pluhař, Weidenmüller, Zuk, Lewenkopf and Wegner (1995)



- RMT $\rightarrow H(\xi) = H^s + i\left(\pi\xi/\sqrt{N}\right)H^a, \quad \xi = \begin{cases} 0 \text{ for GOE} \\ 1 \text{ for GUE} \end{cases}$

T-Violation Parameter ξ



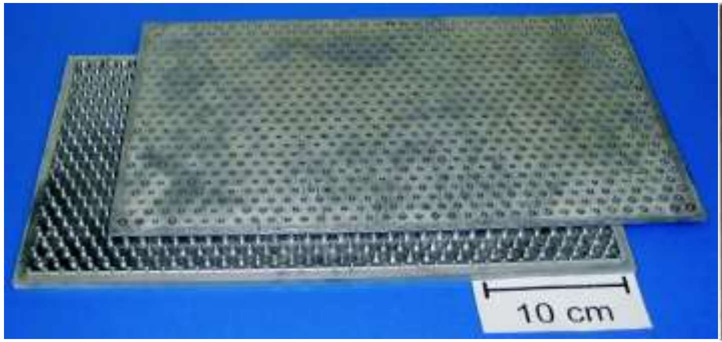
- Largest value of T-violation parameter achieved is $\xi \simeq 0.3$
- Published in Phys. Rev. Lett. **103**, 064101 (2009)

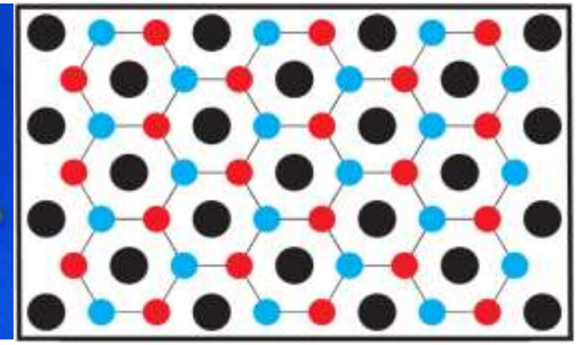
Summary and Outlook

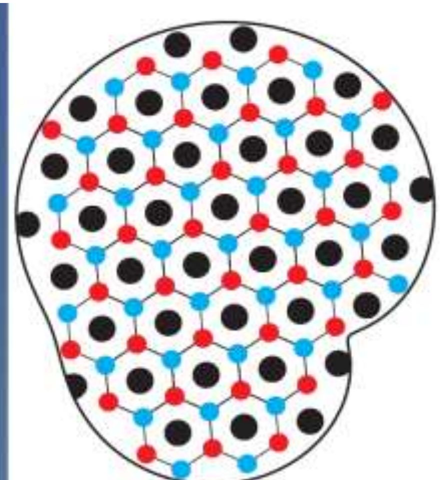
- Ericson fluctuations are a universal phenomenon in mesoscopic systems at all scales and are now considered to be a paradigm of quantum chaos.
- This was not expected when Theo Mayer-Kuckuk worked on Ericson fluctuations in nuclei for which they were conjectured in the early 60ies of last century.
- We are testing presently predictions for quantum chaotic scattering on superconducting open quantum graphs with a sizeable number of bonds and vertices.

- Finally, we are also studying in microwave scattering experiments spectral properties in regular and chaotic superconducting Dirac billiards modelling Graphene and a Fullerene C_{60} molecule, respectively.

Various Dirac Billards: “Artificial” Graphene (regular and chaotic)







Various Dirac Billards: "Artificial" C_{60} Fullerene