Observation of Quantum Decay Dynamics in an Integrated Photonic Chip

Andrea Crespi,[1,2,*] **Francesco V. Pepe,**[3] **Paolo Facchi,**[4,3]**, Fabio Sciarrino,**[5] **Paolo Mataloni,**[5,2] **Hiromichi Nakazato,**[6] **Saverio Pascazio**[4,7,3] **and Roberto Osellame**[2,1]

[1] *Dipartimento di Fisica - Politecnico di Milano, p.za Leonardo da Vinci 32, 20133 Milano, Italy*
[2] *Istituto di Fotonica e Nanotecnologie - Consiglio Nazionale delle Ricerche (IFN-CNR), p.za Leonardo da Vinci 32, 20133 Milano, Italy*
[3] *INFN, Sezione di Bari, via Orabona 4, 70126 Bari, Italy*
[4] *Dipartimento di Fisica and MECENAS - Università di Bari, via Orabona 4, 70126 Bari, Italy*
[5] *Dipartimento di Fisica - Sapienza Università di Roma, p.le Aldo Moro 5, 00185 Roma, Italy*
[6] *Department of Physics - Waseda University, 3-4-1 Okubo, Shinjuku, 169-8555 Tokyo, Japan*
[7] *Istituto Nazionale di Ottica - Consiglio Nazionale delle Ricerche (INO-CNR), largo Enrico Fermi 6, 50125 Firenze, Italy*

[*] *andrea.crespi@polimi.it*

Abstract: Waveguide arrays, fabricated by femtosecond laser pulses and excited by coherent light, are used to study quantum decay phenomena. By tailoring the system properties, we observe different regimes including quadratic Zeno and power-law decay.

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According to classical physics, the population of an unstable state, coupled to a continuum, evolves following an exponential decay curve. Quantum mechanical predictions are however markedly different [1] (see Fig. 1a). Initially, the survival probability $p(t)$ is quadratic, giving the so-called quantum Zeno regime: $p(t) \sim 1 - t^2/\tau_Z^2$ for $t \to 0$. The constant τ_Z, called Zeno time, is proportional to the coupling strength. Indeed, an approximately exponential decay trend sets on at intermediate times; depending on the system parameters this regime may persist quite for long, but never indefinitely. In fact, the tail of the decay curve follows a power-law $p(t) \propto t^{-\alpha}$, with superimposed oscillations, where the value of the coefficient α depends on the specific Hamiltonian of the system. The latter behavior is predicted under the very general hypothesis that the Hamiltonian is bounded from below [2,3].

The "Zeno" region was successfully observed in experiments conducted on very different physical systems [4–7]. On the contrary, a clear experimental observation of the power-law regime is still lacking. In fact, this regime usually occurs when the preceding exponential decay has strongly depleted the initial state, at a point that makes it hard to further measure the state population in an accurate way.

In this work, we adopt arrays of single-mode optical waveguides to implement quantum systems where a discrete state is coupled and can decay into a continuum (see Fig. 1b-c). The linearly polarized optical modes of the array represent distinct quantum states of the photon. Relative coupling between modes, occurring by evanescent field, is adjusted by acting on the geometrical properties of the array. Changing the effective index of the guided modes, on the other hand, is equivalent to detuning the energy levels. Notably, in this framework the temporal evolution of the quantum system is directly mapped onto the spatial propagation coordinate, thus allowing an easy experimental probing of the system population [8–10].

Waveguides are directly inscribed in a glass substrate by the femtosecond laser micromachining technology [9–11]. We fabricate several structures, optimizing the system parameters in order to investigate diverse decay regimes. The dynamic evolution of the system is experimentally retrieved by injecting laser light at the array input, and by acquiring with high dynamics the light scattered from the waveguides along propagation. In case the discrete state is weakly coupled to the continuum, we observe the quadratic Zeno region, followed by the well-known exponential decay. If the coupling is increased and the other parameters of the system are judiciously tuned, we are able to observe experimentally the power-law decay at long evolution times (Fig. 1d).

These results open novel perspectives in the study of quantum decay. The present method may be adopted for the experimental investigation of more complex interactions between a system and its environment, as well as to observe non-Markovian dynamics.

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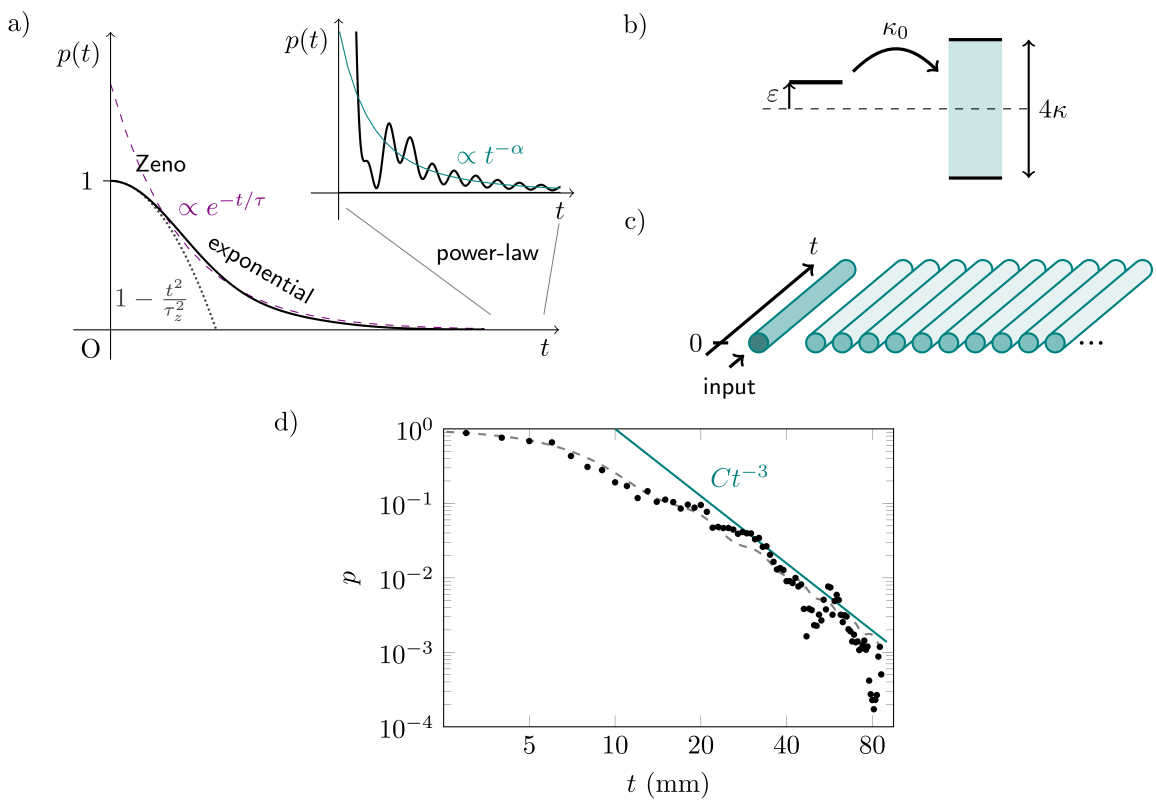

Fig. 1. a) Typical temporal evolution of the survival probability $p(t)$ for a discrete quantum state coupled to a continuum. In particular, our study refers to the system represented in (b): a discrete energy level with detuning ε coupled (by a coupling coefficient κ_0) to a continuum band of width 4κ. This system is implemented optically with an array of single-mode waveguides (c). Panel (d) reports the experimentally measured survival probability (black dots) for a system with $\kappa_0 \simeq 0.89\kappa$ and $\varepsilon \simeq 0.76\kappa$, where the power-law decay is evident at long evolution times. Numerical simulation of the same system (gray dashed line) and a power-law curve $\propto t^{-3}$ are also plotted for comparison.

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