50 years of optical tunneling

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Preface

50 years of optical tunneling

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'… *the triumphant vindication of* ***bold*** *theories—are these not the pride and the justification of our life's work*?'– Sherlock Holmes, in 'The Valley of Fear' by Sir Arthur Conan Doyle

The special issue 'Fifty years of optical tunneling' celebrates the fifty-year-anniversary of the seminal paper by L V Keldysh, 'Ionization in the field of a strong electromagnetic wave', published in November 1964 in Russian [1] and then, in May 1965, in its English translation [2].

When a laser field interacting with an atom is weak, the conventional perturbation theory allows us to understand and describe almost everything. But what should one do if the energy of the electron oscillations in the laser field exceeds the photon energy and approaches the electron binding energy? What if the strength of the laser electric field starts to approach the strength of the Coulomb field that binds an electron inside an atom?

In other words, what should one do when the conventional perturbation theory is no longer applicable? Here is a short answer: one should go and read the Keldysh paper.

It provides both the mathematical tools and the physical picture for interpreting the mathematical results. It provides the fundamental understanding of the very rich dynamics that can be triggered by intense laser field. It also shows the deep connection between multi-photon ionization of atoms and molecules and the multiphoton valence-conduction band transitions inside dielectrics, a connection which we are now beginning to appreciate more and more.

Reviewing the Russian literature of the late 19th century, Eugene-Melchior de Vogüé (1848–1910), a French diplomat and literary critic, wrote in his 'Le Roman Russe': '…*Nous sommes tous sortis du* Manteau *de Gogol*'. Similar is the relationship between the theory of intense laser-atom interaction and the Keldysh paper. The fundamental papers by V S Popov and coworkers [3], A Nikishov and V Ritus [4], H Reiss [5], F Faisal [6], N Manakov and L Rapoport [7], and many other papers too numerous to list here, are all deeply linked to the Keldysh paper.

Simply said, the Keldysh paper has laid down the foundation for the whole field of intense-field laser-atom interaction and the many things that have followed. Paraphrasing Plato: '… *good theory gives soul to the Universe, wings to the mind, flight to the imagination, and charm and gaiety to life and to everything*'.

Virtually all effects that have been discovered in this field can be interpreted within the Keldysh theory, or within its modifications. And when a new experimental observation seems to belay its predictions (see e.g. [8]), the initial surprise (see e.g. [9]), usually followed by a flurry of experimental and theoretical activity, often culminates in a clear physical picture that, once again, grows out of the masterpiece painted by Keldysh's bold brush.

In 1964, the laser had just been invented. Multi-photon ionization, analyzed in the Keldysh paper in detail, had not yet been observed—but followed shortly [10]. Optical tunneling—one of the key outcomes of the Keldysh analysis, would remain out of reach for another two decades [11]. Above-threshold ionization, predicted by Keldysh, remained unnoticed until its experimental observation [12] in 1979—and even then, the connection to the Keldysh analysis was generally missed for many years. Quantum description [13, 14] of high harmonic generation [15–18] has been followed by the realization that all basic expressions flow directly from the Keldysh theory.

The recollision picture [19–21], which grew out of the semiclassical interpretation of the Keldysh theory [22], has given both solid and also intuitive foundation to its generalizations. These have allowed us to understand many puzzles, such as the surprising efficiency of multiple ionization [23, 24], which exceeded the predictions of simple theory by many orders of magnitude. The list goes on…

The Keldysh paper has taught us many lessons. Keldysh began the theoretical analysis of strong field ionization as purely academic research into the fundamentals of intense laser–matter interaction, decades before the laser intensities required to observe 'optical tunneling' became available. Who would have expected that this hard-core theory, developed for a seemingly impractical range of experimental parameters, would eventually lead to new applications and new technologies?

Yet, this is precisely what is now happening, several decades after the paper was published. 'Optical tunneling' has led to new ways of imaging ultrafast electronic and nuclear dynamics [25–30] and new table-top sources of bright coherent XUV emission based on high-harmonic generation [31], which are finding increasingly large numbers of applications. The technology to generate attosecond pulses is just one among those applications. The fundamental physics of multiphoton transitions in transparent materials is at the core of laser machining of dielectrics, corrective eye surgery with infrared lasers, new methods of generating terahertz radiation, etc.

The Keldysh paper proves that fundamental physics is not only beautiful—it is also useful, even if it is hard to immediately predict what exactly its uses will be. And it takes time to figure it out.

It also often takes time to fully appreciate the impact of a breakthrough work. When one looks at the citations of the Keldysh paper, one sees that it took almost forty years before its impact was fully appreciated (see figure 1). Humans can be maddeningly slow.

The Keldysh paper also teaches us how theoretical physics can be so much like mathematics, and yet so very different. Keldysh's is the quintessential *bold* theory.

Its main approximation is to completely ignore the effect of the atomic potential on the electron motion in the continuum. From a purely mathematical standpoint, this approximation violates every rule in the theory book. It makes the results gauge-dependent. That's a *no*—physical observables should not depend on the gauge. It makes the continuum states of the electron non-orthogonal to the bound states. That is also a *no*. If treated as the first-order term in the expansion in powers of electron–core interaction, it leads to the series that does not converge—yet another red flag.

To summarize, from a purely mathematical standpoint, this theory is so far from perfect in so many ways that *Sov. Phys.—JETP* could have rejected it outright. We are so glad it did not! The physical picture that stands behind it is so intuitive, clear, and compelling that the theory not just works—it works very well, and it continues to give us the guiding light to this day. It is the beauty of this light that we are celebrating today.

The special issue offers an overview of the different facets and applications of optical tunneling and its implications for modern science, both in fundamental studies of intense laser–matter interaction and in ultrafast optical technologies, while at the same time indicating how these studies are likely to evolve in the

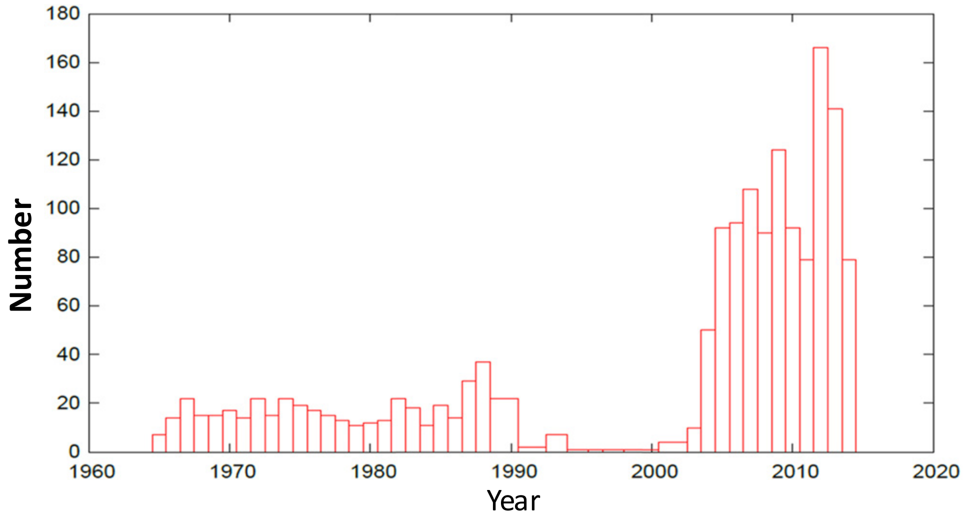

Figure 1. Number of citations of the Keldysh paper [1], based on 'Web of Science' data.

coming years. It includes a review on the history and present status of the Keldysh theory, and a tutorial on photoemission delays. Research papers by recognized experts cover a variety of topics including strong-field ionization, high-harmonic generation, strong-field photoelectron spectroscopy, and strong-field control in atoms, molecules, and solids. We hope that this collection will guide exciting new research in the future.

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