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Simone Gargiulo

Electromagnetic Processes of Nuclear Excitation

From Direct Photoabsorption to Free Electron and Muon Capture

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Electromagnetic Processes of Nuclear Excitation

From Direct Photoabsorption to Free Electron and Muon Capture

Doctoral Thesis accepted by
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Author
Dr. Simone Gargiulo
Institute of Physics (IPhys)
École Polytechnique Fédérale de Lausanne (EPFL)
Lausanne, Switzerland

Supervisor
Prof. Fabrizio Carbone
Laboratory for Ultrafast Microscopy and Electron Scattering
Institute of Physics (IPhys)
École Polytechnique Fédérale de Lausanne (EPFL)
Lausanne, Switzerland

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Sometimes it is the people no one can imagine anything of who do the things no one can imagine.

—Alan Turing

To my parents, whose endless efforts and altruism have made my accomplishments possible, and to all those who have shaped who I am today.
I am deeply grateful for your encouragement, support, and patience as I followed my dream of becoming a scientist.

Supervisor's Foreword

Recent technological advances allowed for the manipulation of material's properties in out-of-equilibrium conditions. In this thesis, the possibility of applying these methods to control nuclear phenomena is addressed both theoretically and experimentally. When a free electron is captured by an ion having a vacancy in one of its deep core-levels, if the energy of the electron plus the binding energy of the capturing orbital matches one of the atom's nuclear excitations, an isomeric transition can be induced. In this thesis, it has been shown theoretically that if the capturing ion's electronic structure is out of equilibrium, the cross section of such effect can be enhanced. In a separate work, it has also been shown that it is possible to further enhance such a cross section if the wavefunction of the free electron is engineered prior to the capture to better match the energy-momentum conservation of a specific orbital. Building on these ideas, a new effect is also proposed by exploiting the possibility for any neutral ions to capture muons in one of their naturally empty muonic orbitals, potentially yielding nuclear excitations at much higher energies, in the order of MeV. These results offer a new perspective on the possibility to use modern tools to control the nuclear properties of matter. To implement these ideas, a new instrument has been developed and described in this thesis, aiming at measuring the fluorescence of excited nuclei upon a pulsed excitation. Currently, it is commonly assumed that a laser-driven plasma can be used to generate X-rays to directly photoexcite a nuclear transition. This thesis reports an extensive experimental campaign aiming at reproducing and benchmarking this effect, and shows that the process reported in the literature cannot be ascribed to a nuclear transition. Furthermore, an extensive modeling of the data is provided, offering a quantitative perspective of the excitation probabilities of nuclei in a laser-driven plasma scenario. Overall, this thesis provides a historically accurate description of the electromagnetic excitation mechanisms of isomers and

reports theoretical and experimental original research aimed at discussing the feasibility and perspective of their active manipulation. These results have implications for both the discovery of novel methods for nuclear energy harvesting and storage, and for fundamental research in nuclear physics.

Lausanne, Switzerland
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Fabrizio Carbone

Abstract

In the vast expanse of the Universe and on our planet, nuclei exist in a state of excitation. These nuclei, known as nuclear isomers, possess unique properties that make them play a crucial role in diverse domains of physics. In nucleosynthesis, the process by which new atomic nuclei are formed inside stars, isomers can influence the rates of nuclear reactions, leading to variations in the production and abundance of elements we see around us. Additionally, some isomers hold potential applications in nuclear technologies, including the energy sector. These excited nuclear states can persist for varying periods, from fractions of a second to billions of years and beyond, before decaying to their ground state. If harnessed, feeding and depleting these isomers could represent a clean and high-density way to store and release energy on demand. The quest for efficient dynamical population control of nuclear isomer has long captivated the imagination of physicists, yet this elusive goal remains beyond our grasp.

In this dissertation, I examine the potential of employing nuclear excitation mechanisms as viable tools for achieving such manipulation. Several processes of nuclear excitations from both theoretical and experimental perspectives are explored: direct photoabsorption, nuclear excitation by electron capture (NEEC), and nuclear excitation by free muon capture (NEμC).

This thesis begins by delving into the historical framework of nuclear excitation by electron capture (NEEC), a process that was proposed in 1976 and is yet to be comprehended. A recently claimed observation has sparked new interest in nuclear excitation processes as a way to release the energy trapped in isomers. However, the irreconcilability between the first observation, the theoretical framework, and the recent repetition of the experiment reveals that much remains to be learned.

Regardless of the specific process being examined, the primary goal is to increase the likelihood of their occurrence. One such possibility involves NEEC taking place in excited ions, where the screening effect of other electrons provides nearly resonant orbitals where capture can occur. This process was initially proposed to mitigate the discrepancy between the experimental finding and the theoretical prediction. In this new setting, three orders of magnitude increase in the NEEC cross sections for ^{73}Ge is found theoretically. Another approach enabling the manipulation of the NEEC cross

section involves engineering the electron wavefunction that undergoes capture. This technique not only demonstrates an increased occurrence of NEEC but also highlights the potential to alter the shell where the highest capture takes place.

The second mechanism, NEμC, occurs in exotic muonic atoms. The process is introduced as a counterpart to NEEC, with the electron being replaced by a muon. It follows a presentation of the framework within which this process has emerged and how it changes the paradigm in comparison to NEEC. Owing to the increased proximity of muons to the nucleus, this process has been found to exhibit cross sections that are several orders of magnitude higher than NEEC for excitations in the MeV range. By examining the unique properties of NEμC, insights into the process and its potential applications are provided, including muon-induced fission.

Lastly, nuclear excitations are studied in the context of a laser-generated plasma scenario, where nuclei might be excited through the resonant absorption of a photon, together with other competing processes (such as inelastic electron scattering). The design and implementation of a tabletop setup for generating keV-hot plasma upon femtosecond laser irradiation are presented. The experimental work has been conducted on a ^{181}Ta target using a time-dependent X-ray spectroscopic technique. The absence of a clear decay signal raises the question of whether the excitation of the ^{181m}Ta isomer has ever been observed in this context.

This dissertation aims to deepen the understanding of nuclear excitation mechanisms, emphasizing their complexities and potential for both further fundamental research and practical applications. Throughout the chapters, various ideas are mentioned for future research that could expand the scope of the physics here discussed.

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To create freedom for oneself and also a sacred No to duty: for that, my brothers, the lion is required. To take the right to new values—that is the most terrible taking for a carrying and reverent spirit. [...] The child is innocence and forgetting, a new beginning, a game, a wheel rolling out of itself, a first movement, a sacred yes-saying.

Three metamorphoses of the spirit I named for you: how the spirit became a camel, and the camel a lion, and finally the lion a child.

—Friedrich Nietzsche, Thus Spoke Zarathustra

This has been a fantastic journey! Let's be clear, it has been challenging and full of uncertainties, and the contentment does not certainly come from having completed it. I am grateful as I have learned a bit more about myself and the world that surrounds me—hopefully undergone a metamorphosis of the spirit. Nonetheless, the path toward the spirit of a child—taking the right for oneself to create new values—is only at the beginning.

I slowly realized, over the years, how vital the care and attention my parents had during my childhood was. The certainty of always having them by my side has been the anchor and security that allowed me to devote myself to the pursuit of my passions. To them goes my greatest gratitude; for the years they spent chasing after me and making me a better person. I thank them for the warm, bonded family they have given to me and my siblings. I thank my sister Sara and my brother Costantino. Growing up together has been surely one of the best parts of my life, which I look back on with nostalgia. Thanks for your patience and comprehension.

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in me. These years would not have been the same without you. “If I am really able to care for the sticky little leaves I shall only love them, remembering you”. *Te voglj ben overamente.*

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claimed it was entry-level. When I think of you, I associate you irretrievably with Barberousse or the bicycle ride home on a winter night and, of course, with food.

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