

# Advances in X-Ray Spectroscopy of Laser Plasmas

Online at: <https://doi.org/10.1088/978-0-7503-3375-7>



# Advances in X-Ray Spectroscopy of Laser Plasmas

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**IOP** Publishing, Bristol, UK

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ISBN 978-0-7503-3375-7 (ebook)  
ISBN 978-0-7503-3373-3 (print)  
ISBN 978-0-7503-3376-4 (myPrint)  
ISBN 978-0-7503-3374-0 (mobi)

DOI 10.1088/978-0-7503-3375-7

Version: 20200701

IOP ebooks

British Library Cataloguing-in-Publication Data: A catalogue record for this book is available from the British Library.

Published by IOP Publishing, wholly owned by The Institute of Physics, London

IOP Publishing, Temple Circus, Temple Way, Bristol, BS1 6HG, UK

US Office: IOP Publishing, Inc., 190 North Independence Mall West, Suite 601, Philadelphia, PA 19106, USA

*In memory of recently passed away*

*A Ya Faenov*

*with appreciation of his truly outstanding contribution  
to the experimental spectroscopy of laser-produced plasmas.*



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# Author biography

## Eugene Oks

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**Eugene Oks** received his PhD degree from the Moscow Institute of Physics and Technology, and later the highest degree of Doctor of Sciences from the Institute of General Physics of the Academy of Sciences of the USSR by the decision of the Scientific Council led by the Nobel Prize winner, academician A M Prokhorov. According to the Statute of the Doctor of Sciences degree, this highest degree is awarded only to the most outstanding PhD scientists who founded a new research field of a great interest. Oks worked in Moscow (USSR) as the head of a research unit at the Center for Studying Surfaces and Vacuum, then—at the Ruhr University in Bochum (Germany) as an invited professor, and for the last 30 years—at the Physics Department of the Auburn University (USA) in the position of Professor. He conducted research in five areas: atomic and molecular physics; plasma physics, laser physics; nonlinear dynamics; and astrophysics. He founded/co-founded and developed new research fields, such as intra-Stark spectroscopy (a new class of nonlinear optical phenomena in plasmas), masing without inversion (advanced schemes for generating/amplifying coherent microwave radiation), and quantum chaos (nonlinear dynamics in the microscopic world). He also developed a large number of advanced spectroscopic methods for diagnosing various laboratory and astrophysical plasmas—the methods that were then used and are used by many experimental groups around the world. He has published about 450 papers and 7 books, including the books *Plasma Spectroscopy: The Influence of Microwave and Laser Fields*, *Stark Broadening of Hydrogen and Hydrogenlike Spectral Lines in Plasmas: The Physical Insight*, *Breaking Paradigms in Atomic and Molecular Physics*, *Diagnostics of Laboratory and Astrophysical Plasmas Using Spectral Lineshapes of One-, Two, and Three-Electron Systems*, *Unexpected Similarities of the Universe with Atomic and Molecular Systems: What a Beautiful World*, and *Analytical Advances in Quantum and Celestial Mechanics: Separating Rapid and Slow Subsystems*. He is the Chief Editor of the journal *International Review of Atomic and Molecular Physics*. He is a member of the Editorial Boards of two other journals: the *Open Journal of Microphysics* and the journal *Open Physics*. He is also a member of the International Program Committees of the two series of conferences: Spectral Line Shapes, as well as Zvenigorod Conference on Plasma Physics and Controlled Fusion.

# Chapter 1

## Introduction

This book presents advances in x-ray spectroscopy of:

- plasmas interacting with a laser radiation;
- laser-induced plasmas.

We focus mostly (but not exclusively) in advances in x-ray spectroscopic diagnostics. These advances are mainly due to the progress in theoretical and experimental studies of the shapes of x-ray spectral lines. The primary reason is that the spectral line shapes are practically independent of the choice of a particular model of the plasma state. This is a clear distinction from other diagnostics that depend on the choice of the plasma state, which could result in a large uncertainty.

The first theoretical underpinnings for analyzing x-ray spectra for plasma diagnostics were developed for astrophysical purposes. It is considered that the beginning of the observational x-ray astrophysics dates to the year 1962 where x-ray binary source Scorpius X-1 was discovered [1]. In the intervening dozens of years, tremendous progress has been made in observational x-ray astrophysics—see, for example, review [2] and references therein. X-ray spectroscopy enables studying a wide variety of astrophysical objects. In particular, diagnostics based on x-ray spectral lines are used, for instance, for measuring densities, temperatures, ionization balance, and abundances—see, for example, review [3] and references therein.

These techniques were further developed and used for diagnostics of various laboratory plasmas. X-ray spectroscopy is a set of multi-parameter methods for plasma diagnostics. In its traditional form it can provide information, for example, about the electron density, the temperature of electrons and ions, the densities of radiating atoms and ions, and the ionization balance—see, for instance, review [4], as well as book [5] and references therein.

The most fruitful results in the traditional x-ray diagnostics of laser plasmas were achieved due to advances in the theory of the Stark broadening of ion spectral lines in plasmas—see, for example books [6–9]. A brief overview of some of these

theoretical advances is presented in appendix A of the current book. These advances provided opportunities for relatively accurate measurements of the electron density, as well as of the temperature of electrons and ions.

More recent advances in theoretical and experimental laser plasma diagnostics based on the x-ray spectral line shapes have significantly expanded the scope of measured parameters—see, for instance, book [9] and references therein. It became possible to study the development of Langmuir waves, ion acoustic waves, and transverse electromagnetic waves induced by various laser–plasma interactions. Also, these advances enabled the possibility to study other nonlinear processes caused by laser–plasma interactions, such as, for instance, parametric decay instabilities. Last, but not least: it has also become feasible to obtain information about the rates of charge exchange between multicharged ions—information virtually inaccessible for other methods. Details on all of these advances can be found in papers [10–35] (listed in chronological order) and are presented in the current book.

Additional important information can be obtained through the polarization analysis of x-ray spectral line shapes. These methods, presented in papers [36–38] were developed for powerful Z-pinchs, but they are applicable also for laser plasmas.

The practical importance of this entire research area is the following. First, it is indispensable for one of the two major directions in the quest for controlled nuclear fusion—namely, for laser fusion. Second, it is an important tool in studying matter under the extreme conditions produced by super-high-intensity lasers. Third, it can provide atomic reference data (such as the rate of charge exchange between multicharged ions) virtually inaccessible by other methods. Fourth, it shows the way to creating plasma-based tunable x-ray lasers. Fifth, it opens up new avenues for laboratory modeling of physical processes in astrophysical objects and a better understanding of intense laser–plasma interactions.

This book is structured as follows. Chapter 2 presents theoretical and experimental studies of charge-exchange-caused dips (X-dips) in profiles of x-ray spectral lines. It also presents the application of the X-dip phenomenon to the experimental determination of rate coefficients of charge exchange between multicharged ions in plasmas.

Chapter 3 is devoted to diagnostics of non-relativistic laser–plasma interactions based on their effects on x-ray spectral line shapes. Most of the attention is given to the phenomenon of Langmuir-wave-caused dips (L-dips) and their applications to measuring parameters of plasmas and of the laser- or laser-caused-fields in plasmas.

Chapter 4 presents theoretical and experimental studies of relativistic laser–plasma interactions based on their effects on x-ray spectral line shapes. The corresponding diagnostics provide, in particular, experimental information about various nonlinear processes in plasmas, such as, for example, the parametric instabilities.

In chapter 5 the discussion is focused on the possibilities of spectroscopic measurements of GigaGauss or multi-GigaGauss magnetic fields, developing during interactions of plasmas with super-intense laser radiation. These possibilities have

employed effects of these ultra-intense magnetic fields on the locations and width of L-dips in x-ray spectral line profiles.

Chapter 6 presents concluding remarks. It includes a brief description of several works that did not fit in the scope of chapters 2–5.

The appendices provide additional details on the topics presented in chapters 2–6.

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