

Chapter 1

Introduction: What Is This Book About?

Abstract We present the main ideas of the book and describe the contents of the book in detail.

1.1 Main Ideas

Many recent publications devoted to the interaction of photons and electrons with atoms and molecules have the same structure. In the first step, a general quantum-mechanical formula for the cross section is given. In the next step, the most “accurate” numerical functions for the bound-state electrons are employed. Since the binding energies can be measured with high accuracy, the wave functions pass the test for reproducing the binding energies with a good accuracy. In the last step, the computer is put to work. Sometimes, attempts are made to include interactions between the electrons in the final state.

About thirty years ago such an approach was justified to some extent. Most calculations were connected with characteristics that could be detected experimentally. In such experiments energies of the order of the electron binding energies were transferred to the targets. There was no small parameter, and thus there was no possibility to evaluate the equations determined by the original formalism of quantum mechanics. The theoretical atomic physics was indeed becoming a science of precise computations. The near-threshold behavior of processes in which one could find a small parameter was rather an exception.

The situation changed at the end of 1980s, when new synchrotron sources of photons became available. Experiments involving photon energies of order about 10 keV were carried out. For light atoms, such energies are much larger than the binding energies. Some of theoretical calculations which could be of practical importance now contained a small parameter.

In the early years of quantum mechanics, Bethe [1, 2] described the main features of high-energy electron–atomic scattering; see also [3]. Here “high energy” means that the energy greatly exceeds the binding energy of the system. Thus, for example, an energy of 1 keV can be considered a “high energy” for an atom of hydrogen, but not for the K electrons of a neon atom. The main principles of high-energy

atomic physics were developed and employed later in the papers of our teacher V.G. Gorshkov and his collaborators (references will be given throughout the text). These principles can be extended to the analysis of any interaction between high-energy charged particles or photons with bound systems. They are as follows:

- The differential cross section of a high-energy process is enmeshed in the kinematic region, where the same process on the free electrons is allowed.
- Each act of exchange by large momentum q strongly exceeding the characteristic momentum μ_b of a bound system leads to a parametrically small factor.
- The interactions between the fast and slow participants of the process can be treated as a perturbation.
- The cross sections can be expressed in terms of certain parameters of the bound systems.

1.2 Subject Matter

In this book we show how these ideas work. In addition to the standard techniques of quantum mechanics, we employ the Lipmann–Schwinger equation (LSE) [4], which allows us to find the Fourier transforms of wave functions in terms of the wave functions at small distances. We use also Feynman diagrams, which can be viewed as graphical illustrations of the LSE. Employing Feynman diagrams for describing the bound electrons became possible due to the work of Furry [5]. The kinematic region where the momentum transferred to the nucleus, known also as the recoil momentum, can be made small ($q \sim \mu_b$) is called the *Bethe ridge*. In many cases the Bethe ridge provides the main contribution to the cross section. The characteristics of a process on the bound electrons at the Bethe ridge can be expressed in terms of those for the same process on free electrons. This makes the investigation of a process on free electrons a necessary step of theoretical analysis. Such an analysis carried out before beginning computations helps to avoid numerous possible mistakes. Unfortunately some of the latter can be found in published papers. These points are the subject of Chap. 2.

In Chap. 3, we show how the perturbative treatment of fast electrons should be carried out. Although looking to be simple, the perturbative approach was not always carried out properly. Validity of the perturbation expansion does not necessarily mean that the lowest-order approximation is sufficient even for a qualitative description of a process. We demonstrate that in processes with large momentum q transferred to the nucleus, the lowest-order term of perturbative series should contain the plane wave and the first-order Coulomb correction. We also develop the perturbative approach to the final state interaction (FSI) of a fast ejected electron with the atomic shell [6]. We demonstrate that the lowest-order FSI correction should include the terms describing one and two interactions between the fast electron and the atomic shell. The amplitude of the process contains infrared divergent terms that cancel in the expressions for the differential and total cross sections.

In Chap. 4, we demonstrate that $2 \rightarrow 3$ processes with large recoil momenta are described by triangle diagrams, with the main contributions determined by the anomalous singularities of the latter [7]. This enables us to obtain analytical expressions for the differential distributions and for the cross sections. The transfer of large momentum between the electron and the nucleus or between electrons is related to the small values of the corresponding distances, where the shape of the wave functions is determined by the Kato cusp conditions [8]. We explain the importance of the latter and construct the electron wave functions on the coalescence lines.

In Chap. 5, we consider processes in the Coulomb field in the framework of non-relativistic approximation. We introduce a technique that simplifies the calculations in the Coulomb field [9]. We apply it to calculation of the first- and second-order processes. In other words, we calculate the differential distributions and the total cross sections for the photoeffect and also for the Rayleigh scattering, for the Raman scattering, and for the Compton effect.

In Chap. 6, we find the relativistic electron Coulomb functions as power series in $(\alpha Z)^2$ with the Furry–Sommerfeld–Maue functions as the lowest-order approximation [10]. The results are employed for calculation of the photoionization angular distribution and the cross section with inclusion of the terms of order $\alpha^3 Z^3$. We consider also second-order processes. We study the role of various mechanisms for photon elastic scattering on atoms. We present the characteristics of the Compton scattering on the Bethe ridge with inclusion of the $\alpha^2 Z^2$ terms. Employing the results of Chap. 4, we calculate the differential distributions for the Compton scattering outside the Bethe ridge.

In Chap. 7, we analyze the photoionization of atoms. We show the possibility of nonrelativistic asymptotic analysis. We demonstrate that the variety of forms of the electron–photon interactions is connected with the gauge invariance of quantum electrodynamics. We show that the asymptotics for photoionization of s states can be calculated in the velocity form by employing plane waves. In the length form one should include also the lowest nonvanishing term of interaction between the photoelectron and the nucleus. The latter should be included in calculations of the asymptotics for ionization of states with $\ell \neq 0$ in both forms. We analyze the Thomas–Reiche–Kuhn sum rules for the case of a nonlocal field. We carry out asymptotic analysis also for the relativistic case. We present a method for inclusion of the screening corrections for the relativistic case near the threshold and far away from it, as worked out in [11]. We demonstrate that inclusion of the correlations beyond the independent particle approximation (IPA) in the framework of the perturbative approach developed in Chap. 3 enables us to remove the discrepancy between the experimental data and the results of the IPA calculations. We show also how inclusion of the IPA breaking effects changes the asymptotic behavior of the photoionization cross sections [12].

Since the nonrelativistic photoionization cross section drops rapidly with an increase of the photon energy, the higher-order processes dominate in the formation of ions at larger values of the photon energy. In Chap. 8, we carry out relativistic analysis of the second-order and third-order processes. If the photon energy is large enough, the Compton scattering becomes the dominant mechanism of ionization.

We show that the seagull term of the nonrelativistic Compton scattering amplitude can be viewed as the contribution of the negative-energy intermediate states in the relativistic amplitude. We find the general equations for the characteristics of the Compton scattering on the Bethe ridge and show their connection with equations of the impulse approximation. Employing the results obtained in Chap. 4, we find the differential distributions outside the Bethe ridge. We demonstrate the infrared stability of the sum of the contribution to the Compton scattering cross section coming from soft scattered photons and the photoionization cross section, which includes the radiative corrections. At still larger photon energies $\omega > \omega_0$, the ions are produced mainly with the creation of electron–positron pairs. We obtain the energy distribution of the electrons ejected due to this mechanism. We calculate the dependence of ω_0 on the value of the nuclear charge Z for the single-electron ions and for the atoms containing Z electrons [13]. We find also the photon energy region where this mechanism dominates in the creation of excited atoms.

In Chap. 9, we consider mainly the double photoionization of the helium atom and of heliumlike ions. We analyze three mechanisms of the process. They are the shake off (SO), final-state interactions (FSI), and the quasifree mechanism (QFM). We study their role in the distribution of photoelectrons and their contribution to the double-to-single cross section ratio $R_0(\omega) = \sigma^{++}(\omega)/\sigma^+(\omega)$, analyzing their dependence on the nuclear charge. We suggest the perturbative model for the description of correlations between the bound electrons in which the electron interactions are treated perturbatively, while their interactions with the nucleus are included exactly [14]. Special attention is devoted to the quasifree mechanism, which was also first considered in [14]. The QFM is at work only beyond the dipole approximation. It manifested itself in experiments on the recoil momentum distribution at photon energies $\omega \approx 800$ eV [15]. It modifies the shape of the spectral curve at energies of several keV. We demonstrate that the approximate wave functions employed in computations of the spectrum at these energies should satisfy the second Kato cusp condition. Otherwise, they can yield a qualitatively incorrect result. At energies of several hundred keV, the QFM dominates in large part of the energy distribution of the photoelectrons. It is also the main mechanism of breaking the nonrelativistic high-energy asymptotics of the ratio $R_0(\omega)$.

In Chap. 10, we study photoionization of fullerenes and of fullerenes with encapsulated atoms. We present the calculation for the photoionization cross section of negative ions C_{60}^- , describing the field of the fullerene shell by the Dirac bubble potential. Investigation of dependence of the high-energy asymptotics on the shape of the model potential is carried out. We analyze the photoionization of atom encapsulated into the fullerene. The energy-dependence of the cross section may differ fundamentally from that for an isolated atom due to interference of the outgoing electron wave with that reflected by the fullerene shell [16]. We analyze the inelastic processes in the fullerene shell that accompany the photoionization of the encapsulated atom. It appears to be possible to sum the perturbative series for photoelectron interaction with the fullerene shell [17]. The probability of inelastic processes was found to be close to unity in the large interval of the photon energies.

Since electron and positron scattering on atoms is analyzed in detail in numerous books, we do not consider those processes in our book (although some aspects of electron scattering by atoms are touched on). In Chap. 11, we analyze various channels for annihilation of positrons with atomic electrons. Since in the annihilation process a large energy exceeding 1 MeV is released, relativistic analysis is required even in the case of slow positrons. Employing the results of Chap. 6, we study the dominative two-photon annihilation process on the Bethe ridge including the contributions of order $\alpha^2 Z^2$. Using the results of Chap. 4, we investigate this process outside the Bethe ridge. We calculate the characteristics of single-quantum annihilation and of annihilation followed by the knockout of a bound electron to the continuum. In the latter case, the role of the QFM mechanism described in Chap. 9 is important [18]. We consider also annihilation followed by creation of $\mu^+ \mu^-$ pair and annihilation accompanied by the creation of mesoatom.

In Chap. 12, we consider the mutual influence of nuclear and electronic transitions. We investigate the influence of the electronic shell on the energy distribution of electrons ejected in nuclear β decay, employing the approach presented in Chap. 3. We demonstrate how the considered effects manifest themselves in experiments on detection of the neutrino mass. We show how the analysis of interactions between the beta electron and the bound electron in the decay of tritium helped to solve the “heavy neutrino” problem. We present the results for probabilities of the creation of vacancies in the atomic shell in β^- and β^+ nuclear decays [19]. For the case of nuclear γ decays, we analyze the calculations of probabilities of internal nuclear conversion. Using the perturbative model developed in Chap. 9, we calculate the probability for ejection of two electrons from the electronic shell during the same nuclear γ transition. Employing the results obtained in Chap. 4, we clarify the mechanism and calculate the cross section for the nonresonant photoexcitation of the nucleus. We also present an analysis of the less-explored influence of the electronic shell on the probability of α decay.

References

1. H. Bethe, *Ann. Phys.* **5**, 325 (1930)
2. H. Bethe, in *Handbook der Physik*, vol. 24/1 (Springer, Berlin, 1933), p. 273
3. M. Inokuti, *Rev. Mod. Phys.* **43**, 297 (1971)
4. R. Newton, *Scattering Theory of Waves and Particles* (Springer, New York, 1982)
5. J.D. Bjorken, S.D. Drell, *Relativistic Quantum Mechanics* (McGraw-Hill Book Company, 1964)
6. E.G. Drukarev, M.I. Strikman, *Phys. Lett. B* **186**, 1 (1987)
7. V.G. Gorshkov, S.G. Sherman, *Sov. Phys. JETP Lett.* **17**, 374 (1973)
8. T. Kato, *Commun. Pure Appl. Math.* **10**, 151 (1957)
9. V.G. Gorshkov, A.I. Mikhailov, *ZhETF* **44**, 2142 (1963)
10. V.G. Gorshkov, *Sov. Phys. JETP* **20**, 1331 (1965)
11. A.I. Mikhailov, *Sov. Phys. JETP* **71**, 465 (1990)
12. E.G. Drukarev, N.B. Avdonina, *J. Phys. B.* **36**, 2033 (2003)
13. E.G. Drukarev, A.I. Mikhailov, I.A. Mikhailov, K.Y. Rakhimov, W. Scheid, *Phys. Rev. A* **75**, 032717 (2007)

14. M.Y. Amusia, E.G. Drukarev, V.G. Gorshkov, M.P. Kazachkov, J. Phys. B **8**, 1248 (1975)
15. M.S. Schöffler et al., Phys. Rev. Lett. **111**, 0132003 (2013)
16. M.Y. Amusia, A.S. Baltenkov, L.V. Chernysheva, Z. Felfli, A.Z. Msezane, J. Phys. B **38**, L169 (2005)
17. E.G. Drukarev, M.Y. Amusia, JETP Lett. **98**, 471 (2013)
18. A.I. Mikhailov, I.A. Mikhailov, JETP **86**, 429 (1998)
19. E.G. Drukarev, M.B. Trzhaskovskaya, Nucl. Phys. A **518**, 513 (1990)

High-Energy Atomic Physics

Drukarev, E.G.; Mikhailov, A.I.

2016, XIII, 384 p. 55 illus., 5 illus. in color., Hardcover

ISBN: 978-3-319-32734-1