Yu. N. Demkov and L. P. Presnyakov, *An asymptotic approach in the theory of atomic collisions*. Research on the elementary processes involved in atomic collisions is important for the development of atomic and molecular physics in general and also for many applications in plasma physics, quantum electronics, astrophysics, and elsewhere. In the theory of atomic collisions there is an obvious need for effective methods which give clear interpretations of the various processes, which definitely show the effects of the various physical parameters, and which permit accurate practical calculations of cross sections and reaction rates.

In the theory of atomic collisions there is no universal calculation method equivalent (in terms of its results) to the Hartree-Fock method for calculations of atomic structures. The reason is the fundamental difference between problems with a continuous spectrum (collisions) and problems with a discrete spectrum (atomic structure).

The most interesting collisions are the "slow" collisions in which the velocity of the relative motion of the atoms is less than the typical orbital velocities of the electrons. Depending on the nature of the particular process under study, the corresponding upper boundary on the kinetic energy of the atoms can range from a few kiloelectron volts (resonant charge exchange[1]) to several million electron volts (vacancy formation in atomic K shells during collisions). For slow collisions, it is usually not possible to use any standard modification of perturbation theory.

The most important results which have been obtained in the modern theory of atomic collisions can be credited to the asymptotic approach. In this approach, the multiple-channel problem of scattering and quantum transitions is broken up into two parts: 1) an identification of the natural physical parameters which are large in magnitude for each particular type of elementary process, $\lambda \gg 1$ (Table II); 2) the construction of asymptotically exact solutions in the form of power series in the small parameters, $\lambda^{-1} \ll 1$. According to the Born–Fock theory, "fast" and "slow" (nuclear) subsystems are singled out in the system of colliding atoms. If the electron terms are classified on the basis of symmetry, selection rules can be written for the quantum transitions. The problem can be simplified substantially by reducing the number of possible processes by discarding the "adiabatically blocked" processes (those for which the Massey parameter[1] is much larger than unity and for which the transition probabilities and cross sections are exponentially small). Analysis of the electron terms and the interactions between the various quantum states leads to a distinction between adiabatic and nonadiabatic regions in configuration space. Quantum transitions occur only in the nonadiabatic regions. In the simplest case, only two states interact in each such region, and the multiple-channel problem reduces to a succession of two-channel problems,[2] each of which can be solved analytically with a known accuracy.[1,3-5,10] This fact reflects a hidden symmetry in the system of colliding atomic particles, which follows from the distribution of atomic electrons among shells.

In general, however, the problem is a multiple-channel problem, and fundamentally new solution methods are required. Typical problems of this type which are of practical interest are listed in Table II. An advantage of the asymptotic approach in the analysis of these problems is that a physical model can be constructed (the expansion in powers of the small parameter $\lambda^{-1} \ll 1$ is carried out in the course of the construction of the model). It is thus possible to find an exact analytic solution for the multiple-channel quantum-transition problem.

In process 1, because of the semiclassical nature of the motion of the highly excited electron, the energy spectrum of the electron is approximately equidistant, so that a method can be found for solving exactly the problem of quantum transitions between highly excited levels for an arbitrary external effect on the atom.[6,7] Calculations of the cross sections and rates of collisional transitions are of interest for radio-astronomy study of the distribution of atomic hydrogen with respect to excited states in planetary nebulae. Process 2 is a natural continuation of the first process into the continuum region. It is thus possible to generalize the bound-state models to the continuum, to study the behavior of quasistationary states of a diatomic system, and to study the behavior of the ionization cross sections as functions of the basic physical parameters.[2] One of the theoretical predictions which has been confirmed experimentally is the formation of monoenergetic groups of electrons as the result of ionization. In processes 3, it is physically justified to use short-range potentials taking into account polarization and the finite dimensions of the system,[2] so that the cross sections for these processes can be calculated reliably. Analysis of the charge exchange of multiply charged ions ($Z \gg 1$) with atoms has shown that the dominant process is capture of atomic electrons to excited ion states. The effective cross section is large, increases with the ion charge, and varies little over an extremely broad energy range.[7,8] The experimental data have confirmed the theoretical conclusions and have spurred an effort to develop lasers for the hard UV and soft x-ray ranges.[9]

Study of inelastic processes in atomic collisions has led to the development of fundamentally new methods in quantum scattering theory. Previously unknown classes of time-dependent quantum-mechanical problems have been identified as having exact solutions.[2,6] The asymptotic approach also makes it possible to generalize the traditional methods (contour integrals, reference equa-

TABLE II.

Process	Asymptotic parameter $\lambda \gg 1$
1. Collisional transitions between highly excited atomic states	Main quantum number n
2. Ionization of atoms in slow collisions	Main quantum number n; analytic continuation of its value into the continuum
3. Formation and decay of negative ions in atomic collisions	Ratio of the electron binding energies in the atom and in the negative ion
4. Charge exchange of multiply charged ions with neutral atoms	The ion charge Z
5. Nonresonant charge exchange of protons with complex atoms; electron capture from inner atomic shells	Ratio of the binding energies of the inner-shell electrons to the binding energies of the optical-shell electrons

tions, generating functions, etc.) to multiple-channel processes with nonseparable nonadiabatic regions. The theory worked out for atomic collisions can also be applied to related fields (the shift and broadening of spectral lines, the propagation of electromagnetic waves in dielectrics, etc.). This approach leads to the most graphic description of the physical processes which occur in collisions, shows the effects of the basic parameters, and makes possible the calculations required to analyze the properties of gases and plasmas.

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