2 Electron collisions with atoms

2.1 Introduction

2.1.1 Generalities

An idealized experiment for studying electron collisions with atoms may be described as follows. A beam of n electrons of a fixed momentum $\boldsymbol{p}$ impinges on a gas per unit time per unit area perpendicular to $\boldsymbol{p}$; then one says that the electron beam is characterized by fluence rate (or flux) n. The gas consists of N atoms of a given species A per unit volume; then one says that the gas is characterized by (number) density N of atoms A. Suppose that a detector registers the number of electrons emerging per unit time into an infinitesimal solid-angle element $\mathrm{d}\omega_0$ around the direction given by the polar angles θ_0, φ_0 (called scattering angles) with respect to $\boldsymbol{p}$. The registered number should be proportional to n, N, and $\mathrm{d}\omega_0$, if n and N are small enough to ensure the conditions that (i) no appreciable interactions occur among electrons; (ii) each collision of an electron with an atom occurs independently, i.e., without interference by other atoms; (iii) no appreciable reduction of atoms occur as a result of electron collisions, e.g., by recoil. Under these conditions (which may be called single-collision conditions), the registered number of collisions per unit time is small, and can be expressed as $N[\mathrm{d}\sigma(\theta_0, \varphi_0)/\mathrm{d}\omega_0]\mathrm{d}\omega_0$, where the proportionality factor $\mathrm{d}\sigma(\theta_0, \varphi_0)/\mathrm{d}\omega_0$ has the dimension of area, and is called the differential cross section. The integral

$$\sigma = \int \frac{\mathrm{d}\sigma(\theta_0, \varphi_0)}{\mathrm{d}\omega_0} \mathrm{d}\omega_0 \tag{1}$$

also has the dimension of area, is called the integrated (or total) cross section, and is an index of the probability of collisions regardless of the scattering angles. We shall use the term "cross section" in this sense, and put the adjective "integrated" when it is necessary to prevent misunderstanding; the adjective "total" will be used in a different sense to be described in Section 2.2.

Atoms in a gas are in thermal motion, and we need to consider the influence of the translational motion of atoms. In another experimental setup, atoms in a beam interact with an electron beam. In general, the physics of an individual collision is determined by the relative motion of an electron and an atom, the translational motion of the combined system of the two being irrelevant. This consideration leads to the distinction between the laboratory frame of reference and the center-of-mass frame of reference. Let us assume that all speeds are nonrelativistic. Suppose that, in the laboratory frame, an electron of mass m and velocity $\boldsymbol{v}_\mathrm{e}$ collides with an atom of mass M_A and velocity $\boldsymbol{v}_\mathrm{A}$. The center of mass moves throughout at constant momentum $M_\mathrm{A}\boldsymbol{v}_\mathrm{A} + m\boldsymbol{v}_\mathrm{e}$, and hence at constant velocity $\boldsymbol{v}_\mathrm{c} = (M_\mathrm{A}\boldsymbol{v}_\mathrm{A} + m\boldsymbol{v}_\mathrm{e})/(M_\mathrm{A} + m_\mathrm{e})$. Seen in the center-of-mass frame, the electron velocity is $\boldsymbol{v}_\mathrm{e} - \boldsymbol{v}_\mathrm{c}$, and the atom velocity is $\boldsymbol{v}_\mathrm{A} - \boldsymbol{v}_\mathrm{c}$. The differential cross section $\mathrm{d}\sigma(\theta, \varphi)/\mathrm{d}\omega$ in the center-of-mass frame is defined by stating that the number of electrons emerging into the solid angle element $\mathrm{d}\omega$ around the direction given by the polar angles θ, ϕ is $n\mathrm{d}\sigma(\theta, \varphi)/\mathrm{d}\omega$. Considering the transformation of the variables, one has the relation [68Sch1]

$$\frac{d\sigma_0(\theta_0,\phi_0)}{d\omega_0} = \frac{(1+\gamma^2+2\gamma\cos\theta)^{3/2}}{|1+\gamma\cos\theta|}\frac{d\sigma(\theta,\phi)}{d\omega} \quad , \tag{2}$$

where $\gamma = m/M_A$. Because γ is 1/1836 = $5.4\cdot10^{-4}$ for electron collision with atomic hydrogen, and is smaller with other atoms, the distinction between the center-of-mass frame and the laboratory frame is inappreciable for most purposes, and also compared to the precision of presently available cross-section data. An exception arises when one considers the energy loss of subexcitation electrons, viz., electrons at kinetic energies below the first electronic threshold, passing through a gas [90Ino1, 93Kim1]. Then, the recoil that an atom receives upon elastic scattering is the sole mechanism for the energy loss, and is determined by the momentum-transfer cross section, discussed extensively in Section 2.5.

For more detailed discussion, one must consider the state of the atom left after a collision. Suppose for simplicity that the atom was initially in the ground state. If the atom is left in the ground state, one says that the collision is elastic; then, the scattered electron has a kinetic energy that equals the initial kinetic energy minus the recoil energy, which is generally small as discussed in the preceding paragraph. The (integrated) cross section for elastic scattering is denoted by σ_{el}, which is treated in Section 2.3.

If the atom is left in a state other than the ground state, then one says that the collision is inelastic; then, the scattered electron has a kinetic energy that equals the initial kinetic energy minus the energy transferred to the atom, which includes the excitation energy of the atom and the recoil energy. Suppose that the state is characterized by a set of quantum numbers, s, the (integrated) cross section is called the cross section for the excitation of s, and is denoted by σ_s.

More specifically, when the state s belongs to a discrete spectrum, it is called the discrete-excitation cross section, which is the subject of Section 2.4. When the state s belongs to a continuous spectrum, one or more of the atomic electrons will depart from the atom, leaving an atomic ion; one calls this process ionization. The (integrated) cross section is called the ionization cross section, which is the subject of Section 2.6.

Finally, if an atom was in an excited state before a collision, it is possible that the atom is left in a state with lower energy, for instance, in the ground state; then, the scattered electron will have a kinetic energy higher than the initial kinetic energy. One calls this process a super-elastic collision. If the state of the atom remains the same after a collision, one says that the collision is elastic.

2.1.2 Scope and policy of the present treatment

The present article will presume basic knowledge of atomic physics; whenever the reader is uncertain about a point in atomic physics, he may consult with "Atomic, Molecular, and Optical Physics Handbook" [96Dra1], which presents concise treatments of many topics related to atomic collisions and spectroscopy. We shall focus on electrons of kinetic energies up to a few keV, chiefly for two reasons. First, most of applications of cross-section data concern primarily electrons of those kinetic energies, as summarized in Chapters 78-88 of the Handbook [96Dra1]. Second, when cross sections are needed for electrons at higher kinetic energies, it is generally possible to estimate their values on the basis of cross sections at lower kinetic energies, using elements of the Bethe theory [30Bet1, 71Ino1, 86Bet1].

We shall treat only neutral atoms initially in their ground state. For neutral atoms initially in an excited state, the electron scattering cross section is in general completely different from that for the ground state. Our knowledge about this topic is so severely limited both experimentally and theoretically that a survey of data for atoms in general is unwarranted at present. However, cross sections for atoms in metastable states, required in certain applications, are indeed a topic of extensive studies, as seen in a review of cross sections of metastable states of helium by de Heer et al. [95deH1]. Electron collisions with atomic ions are treated extensively in Chapter 3.

The quality of data for neutral atoms depends very much on their species. More precisely, it depends especially on whether the electronic structure is a closed shell (as in a rare-gas atom) or an open shell. Closed-shell atoms are readily prepared as targets, and simpler to treat theoretically. Open-shell atoms, in contrast, are not straightforward to prepare as target, because they are formed in fine-structure states differing only slightly in binding energies and are also chemically reactive; even in a chemically pure gas, they readily produce dimers, trimers, and other atomic clusters. As a result, the cross section data presented below are in general more trustworthy for closed-shell atoms than for open-shell atoms.

The differing quality of data for different atoms makes it not only impractical to present cross-section data for all atoms in a unified and systematic format, but also seriously misleading to the reader. Sections 2.2-2.5 thus present data only for selected atomic species for which our knowledge is better than for others. Even among the selected atoms, the data quality differs greatly. Therefore, data are presented sometimes in graphs, sometimes in tables, together with a commentary indicating the status of our knowledge.

The present article is intended to serve as a guide for rapid access to cross-section data, rather than for studying cross sections from a basic point of view. Therefore, only a single set of data is presented for each cross section.

2.1.3 Methods for the determination of cross sections

Experimental methods for measuring electron-collision cross sections have been extensively discussed in the literature. Here we remark only on their most salient features. Basically, one can determine cross sections either through an experiment under single-collision conditions ("beam method"as sketched in Subsection 2.1.1) or through analysis of the transport of macroscopic "electron swarms" in a gas, which involves a large number and variety of collision processes. The two approaches are often viewed as competitive, but are really complementary. The beam method, applicable to a wide range of the electron kinetic energy, yields results of successful measurements conceptually clear and straightforward to interpret, but it suffers from the great technical difficulty in the preparation of an electron beam with finely resolved momentum and in the momentum-analysis of scattered electrons; in general, it is also difficult to determine the absolute value of cross sections. The swarm method is experimentally easier in principle, yields absolute measurements of transport properties leading to absolute values of cross sections, but requires a numerical analysis, using either a Boltzmann transport equation or a Monte Carlo simulation. (See Section 2.5 for further discussion.) Its application is also limited to low electron kinetic energies, i.e., in practice to energies not far exceeding the lowest ionization threshold. In summary, the two methods are complementary to each other.

Theoretical methods for evaluating electron-collision cross sections have been a subject of discussion for many decades, as seen in recent representative textbooks [86Fan1, 95McC1, 95Bur1]. Trustworthy ab initio calculations are feasible only in exceptional cases concerning atoms with the simplest electronic structure such as hydrogen, helium, and, to a lesser extent, other rare gases or alkali atoms. More importantly, theory provides general constraints on certain aspects of cross-section data. An example is the Bethe expression for the energy dependence of the (integrated) cross section [71Ino1], applicable at sufficiently high energy. Another example concerns the threshold behavior for the cross section for a specific inelastic process, discussed for instance by Fano and Rau [86Fan1].

Further constraints on the cross section data are provided by what one might call systematics, e.g., by trends of the data on related species, such as those along a row or a column of the periodic table. Physically, the plausibility of the systematics can be understood in terms of the atomic size, the binding energy, and other properties of the electronic structure. However, it is in general difficult to derive the systematics on a rigorous theoretical basis. Many approaches have been made to the evaluation of the systematics using a simplified scheme and usually also some empirical parameters,

as seen for instance in [94Mar1]. Although these approaches are generally subject to questions from a basic point of view, their results often provide an educated guess in the absence of measurements or better theoretical results.

2.1.4 Data sources and data centers

Since the cross-section data for electron-atom collisions are important to many applications including the physics of discharges and plasmas, atmospheric physics, astrophysics, fusion research, and radiation physics, there have been considerable efforts toward compilation and critical analysis of the data. An early survey appears in the treatise by Massey and Burhop [69Mas1]. Recent surveys are Janev [95Jan1], Crompton et al. [91Cro1], and IAEA [95Int1]. The treatment in each of these references focuses on single applied area: Janev [95Jan1] on fusion plasma research, Crompton et al. [91Cro1] on gaseous electronics, i.e., discharges and low-temperature plasmas, and IAEA [95Int1] on radiological physics.

More general surveys occur in Inokuti [94Ino1], including discussions on various aspects of the cross-section determination, both experimental and theoretical, rather than on the data themselves. Perhaps the most general introduction to the literature is seen in McDaniel et al. [85McD1], which presents an extensive bibliography of data collections, bibliographies, review articles, and monographs (but not individual research articles) up to mid-1984 updated by McDaniel and Mansky [94McD1] to cover work up to mid-1992.

Documents presenting data collections are too numerous to be cited, but are readily found in the bibliographies [85McD1] and [94McD1]. The most recent survey of cross-section data for atoms (and also of diatomic molecules) is published by Zecca et al. [96Zec1].

To access data it is valuable to use data centers, as explained by Gallagher [94Gal1]. One of the most active data centers is the Atomic and Molecular Data Unit, Nuclear Data Section, International Atomic Energy Agency, which publishes the International Bulletin on Atomic and Molecular Data for Fusion, and maintains AMDIS (Atomic and Molecular Data Information System) accessible via the Internet at http://www.iaea.org/programmes/amdis/.

2.2 Total scattering cross sections

2.2.1 Generalities

By the term "total scattering cross section" σ_{tot} one means the sum of the (integrated) cross section σ_{el} for elastic scattering and the total inelastic-scattering cross section σ_{inel}, which is in turn the sum of the (total) excitation cross section σ_{ex} and the (total) ionization cross section σ_i. Here σ_{ex} means again the sum of cross sections for all the individual discrete excitation processes possible at the electron kinetic energy. Further, σ_i means the cross section for all possible ionization processes possible at the electron kinetic energy, including every multiplicity and the final state of the resulting ion. More precisely, σ_i here means the sum of the cross sections for single ionization, double ionization, triple ionization, and so forth with the same unit weight; it is sometimes called the *counting* ionization cross section, and is determined in principle in an experiment that scores the number of all ionization events. Another kind of experiments measure the current produced by ionization, and lead to the *gross* ionization cross section, or the *apparent total* ionization cross section, which is the sum of the cross sections for single ionization, double ionization, triple ionization, and so forth with the weights 1, 2, 3, … (The adjective "total" signifying "all

energetically possible" is necessary for precise expression; however, it is cumbersome, and therefore is often omitted when the meaning is clear from the context.) In summary,

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}, \quad (1)$$

and

$$\sigma_{inel} = \sigma_{ex} + \sigma_{i}. \quad (2)$$

To emphasize the idea of including both elastic and inelastic scattering, some authors use the term "grand total scattering cross section" for σ_{tot}.

Experimentally, the total scattering cross section is in principle measurable through attenuation of an electron beam passing through a gas, or through recoil of atoms in a beam target. Measurements of this kind and resulting data are discussed by Bederson and Kieffer [71Bed1]. In general, the quality of data thus obtained should be good for those atoms that can be readily prepared in a gas target, for instance, rare gases, owing to the simplicity of the measurements at least in principle. An example of recent work is seen in the article by Szmytkiwski et al. [96Szm1], who measured σ_{tot} of rare gases (and several molecules) and also reviewed the recent literature.

Alternatively, the total scattering cross section may be evaluated from data for individual cross sections by summation expressed by eqs. (1) and (2). In a lower part of the energy range treated in the present article, the total elastic-scattering cross section usually dominates. At higher electron energies, and certainly at relativistic kinetic energies, i.e., comparable to, or exceeding 511 keV, the total inelastic-scattering cross section will dominate. The latter may be in turn evaluated from individual inelastic-scattering cross sections, as seen for instance in the study by de Heer and co-workers [77deH1, 77deH2, 79deH1], or are under certain circumstances amenable to theoretical evaluation, as seen for instance in [67Ino1, 81Ino1, 94Jai1]. The total scattering cross section is also important in the analysis of cross-section data with the use of dispersion relations, as seen in the work by de Heer and co-workers [76deH1, 77deH1].

2.2.2 Individual atoms

2.2.2.1 Hydrogen

An early survey of data is seen in the work by de Heer et al. [77deH1]. Trajmar and Kanik [95Tra1] reviewed various experimental and theoretical data. We adopt here their recommendations (Fig. 2.2.1 and Table 2.2.1). Recent measurements by Zhou et al. [97Zho1] confirm the data to several percent.

Below the first excitation threshold (10.2 eV), the total scattering cross section σ_{tot} is the same as the elastic-scattering cross section σ_{el}. Generally, σ_{el} decreases with increasing kinetic energy E, and eventually behaves as E^{-1} at high E. The total inelastic-scattering cross section σ_{inel} increases with increasing E with the successive opening of excitation and ionization channels, reaches a maximum around 50 eV, decreases at higher E. However, because of its asymptotic behavior of the form $E^{-1} \ln E$, σ_{inel} dominates over σ_{el} at high E; then, σ_{tot} is nearly the same as σ_{inel}. Consequently, σ_{tot} is a decreasing function of E in general, with a mild modulation around 50-100 eV.

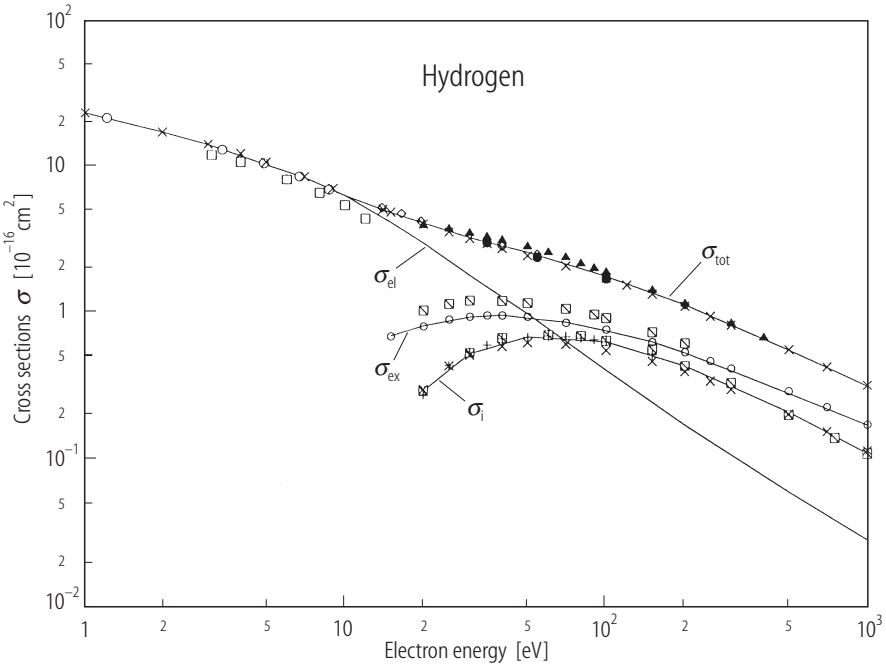

Fig. 2.2.1. Overview of cross sections for H, reproduced with permission from [95Tra1].

Table 2.2.1. Overview of cross sections for H. Data are taken primarily from Trajmar and Kanik [95Tra1]. Janev and Smith [93Jan1] give more detailed tabulations.

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
1	23.0				23.0
2	17.1				17.1
3	14.0				14.0
5	10.2				10.2
7	8.40				8.40
10	6.30				6.30
15	4.15	0.69		0.69	4.84
20	3.00	0.81	0.31	1.12	4.12
30	1.80	0.93	0.53	1.46	3.26
50	0.98	0.93	0.64	1.57	2.55
100	0.40	0.73	0.54	1.27	1.67
200	0.172	0.53	0.38	0.91	1.08
500	0.061	0.28	0.21	0.49	0.55
1000	0.029	0.17	0.11	0.28	0.31

2.2.2.2 Helium

de Heer and Jansen [77deH2] critically examined data on individual cross sections and evaluated σ_{el} and σ_{inel}. Hayashi [81Hay1] also presented recommended values of cross sections. More recently, Trajmar and Kanik [95Tra1], as well as Szmytkowski et al. [96Szm1] and Zecca et al. [96Zec1], reviewed extensive data, both experimental and theoretical. We adopt here the recommendation of Trajmar and Kanik [95Tra1] (Fig. 2.2.2 and Table 2.2.2). The general trend of σ_{tot} is similar to that for atomic hydrogen.

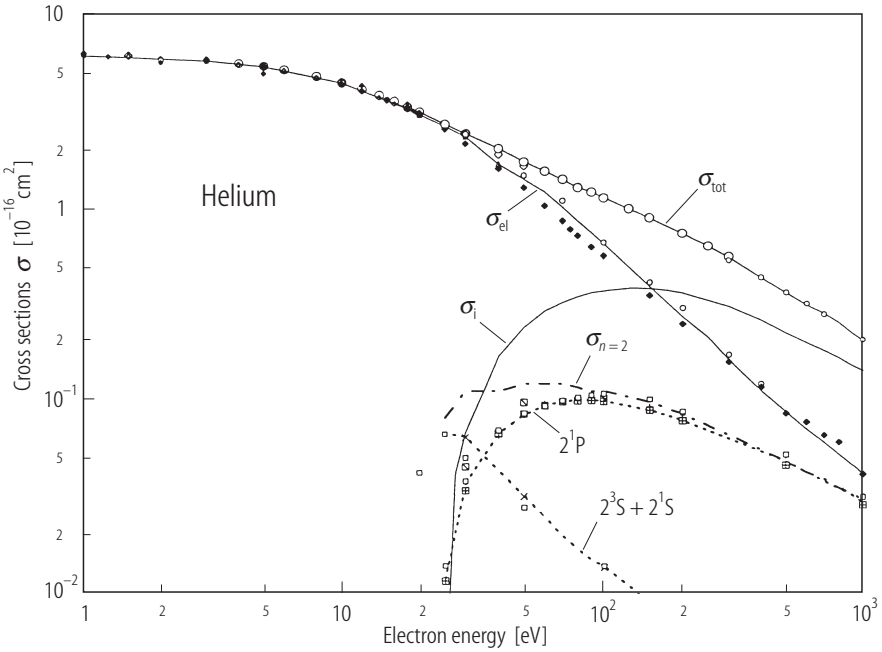

Fig. 2.2.2. Overview of cross sections for He, reproduced with permission from [95Tra1].

Table 2.2.2. Overview of cross sections for He. Data are taken primarily from Trajmar and Kanik [95Tra1], and are augmented by values given by de Heer et al [77deH2] and by Hayashi [81Hay1].

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
1	6.08				6.08
3	5.70				5.70
5	5.30				5.30
10	4.36				4.36
15	3.55				3.55
20	3.00				3.00
25	2.60	0.08		0.08	2.68
30	2.30	0.08	0.07	0.15	2.45
40	1.67	0.17	0.18	0.35	2.02
50	1.40	0.14	0.23	0.37	1.77
60	1.20	0.14	0.29	0.43	1.63

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
80	0.85	0.15	0.35	0.50	1.35
100	0.65	0.16	0.37	0.53	1.18
150	0.39	0.16	0.37	0.53	0.92
200	0.27	0.15	0.35	0.50	0.77
250	0.21	0.14	0.28	0.42	0.63
300	0.16	0.12	0.28	0.40	0.56
400	0.11	0.10	0.24	0.34	0.45
500	0.086	0.074	0.20	0.27	0.36
600	0.070	0.070	0.18	0.25	0.32
700	0.060	0.067	0.16	0.23	0.29
800	0.052	0.061	0.15	0.21	0.26
900	0.046	0.056	0.13	0.18	0.23
1000	0.042	0.050	0.12	0.17	0.21

2.2.2.3 Lithium

As the survey by Zecca et al. [96Zec1] indicates, source data are not only limited in scope and volume, but discordant. The paucity of the data chiefly stems from the difficulty of preparing atomic lithium, in high-temperature vapor, under controlled conditions including a known number density. In particular, current data for σ_{tot} from direct measurements are inconsistent with the sum of individual cross sections. Merely to show the trend of data, we adopt here values of Table 2.2.3, primarily based on the survey by Zecca et al. [96Zec1], with augmentations with the use of the excitation and ionization cross sections given by Wutte et al. [97Wut1] and with extrapolations of σ_{el}. The reliability of the presented data is much less than the data for H and He.

All cross sections are large, i.e., much larger than those for He, and are similar in trends to those of H. This is understandable from the shell structure $1s^2 2s$, with a single electron outside the inner core. However, σ_{inel} dominates over σ_{el} at all electron kinetic energies above 10 eV; the main contributor to σ_{inel} is σ_{ex}, in particular, the cross section for the lowest discrete excitation, viz., the 2s - 2p excitation.

Table 2.2.3. Overview of cross sections for Li. Data are taken primarily from Zecca et al. [96Zec1], and have been augmented by values given by Wutte et al [97Wut1] and by extrapolation.

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
5.4	49	49		49	98
10	40	43	3.9	47	87
20	19	36	4.1	40	59
60	4.5	21	2.2	23	28
100	2.0	13	1.5	15	17
150	1.0	10	1.0	11	12
200	0.5	8.2	0.8	9	9.5

2.2.2.4 Oxygen

According to Itikawa [94Iti1], the only experimental source of σ_{tot} is the measurement by Sunshine et al. [67Sun1]. Their data scatter widely, and are not quite consistent with the sum of individual cross sections adopted by Itikawa and Ichimura [90Iti1]. Note that values of individual cross sections are given also by Laher and Gilmore [90Lah1]. We adopt here values shown in Table 2.2.4, based on the compilations by Laher and Gilmore [90Lah1], Itikawa and Ichimura [90Iti1], Itikawa [94Iti1], and Zecca et al. [96Zec1].

Figure 2.2.3, taken from Itikawa [94Iti], shows σ_{el} and major contributors to σ_{inel} including discrete-excitation cross sections, which are complex in their behavior owing to the multiplet structure of the open shell $2s^2 2p^4$.

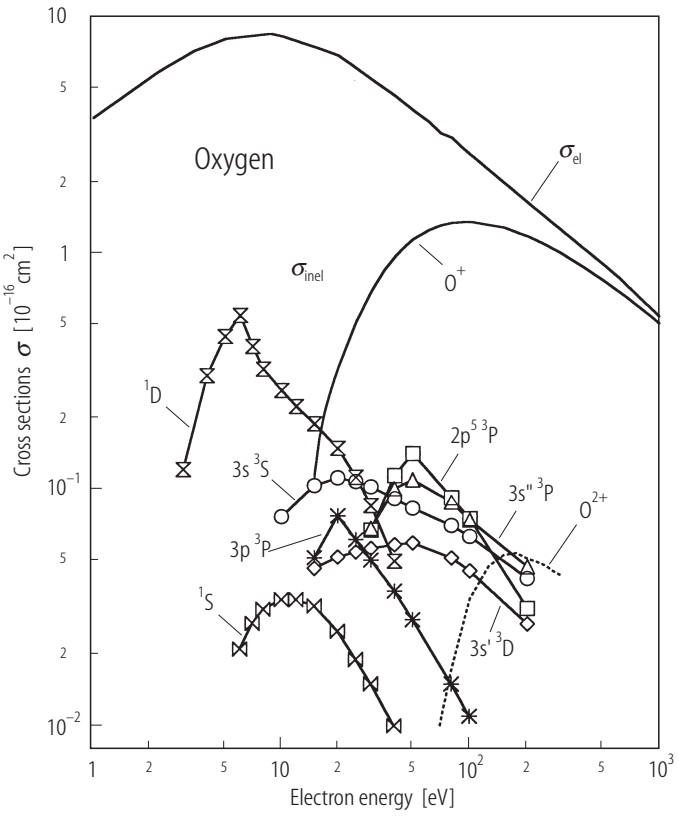

Fig. 2.2.3. Overview of cross sections for O, reproduced with permission from [94Iti1].

Table 2.2.4. Overview of cross sections for O. Data are taken primarily from Laher and Gilmore [90Lah1], Itikawa and Ichimura [90Iti], Itikawa [94Iti1], and Zecca et al. [96Zec1].

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
3.4	7.1	0.2		0.2	7.3
5	7.5	0.3		0.3	7.8
10	8.1	0.3		0.3	8.4
20	6.6	0.7	0.3	1.0	7.6

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
45	4.4	1.1	1.1	2.2	6.6
100	2.6	0.64	1.5	2.1	4.7
200	1.6	0.45	1.3	1.8	3.4
500	0.88	0.19	0.79	0.98	1.8

2.2.2.5 Neon

Soong [76Soo1, 76Soo2] reviewed data on individual cross sections, tested consistency with other information including the oscillator-strength spectrum, and adopted a complete set of inelastic-scattering cross sections, with emphasis on high electron energies. de Heer, Jansen, and van der Kaay [79deH1] also critically examined data of a broader class including σ_{el}, and evaluated σ_{inel}. Notice in particular that de Heer et al. [79deH1] determined the counting ionization cross section σ_i through full consideration of multiple ionization, which is about 5 percent at electron kinetic energies above 200 eV. Hayashi [81Hay1] also presented recommended values. Table 2.2.5 has been prepared after consideration of these earlier recommendations, and represents our adoption. The data should be good to several percent, especially in view of the compatibility of directly measured σ_{tot} with the summed value of individual cross sections within ten percent, except at electron kinetic energies below 100 eV.

Table 2.2.5. Overview of cross sections for Ne. Data are based primarily on de Heer et al. [79deH1] and Zecca et al. [96Zec1].

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
5	2.7				2.7
10	3.3				3.3
15	3.5	0.1		0.1	3.6
20	3.4	0.1	0.1	0.2	3.7
30	3.6	0.1	0.1	0.2	3.8
40	3.4	0.20	0.23	0.43	3.8
50	3.1	0.21	0.30	0.51	3.6
60	2.9	0.17	0.43	0.60	3.5
80	2.6	0.17	0.58	0.75	3.4
100	2.3	0.16	0.68	0.84	3.1
150	1.7	0.14	0.75	0.89	2.6
200	1.4	0.12	0.74	0.86	2.3
300	1.1	0.10	0.72	0.82	1.9
400	0.91	0.083	0.65	0.73	1.6
500	0.77	0.071	0.58	0.65	1.4
700	0.62	0.055	0.41	0.46	1.1
800	0.49	0.051	0.44	0.49	1.0
1000	0.46	0.043	0.33	0.37	0.82
2000	0.29	0.025	0.19	0.21	0.50
3000	0.21	0.018	0.14	0.16	0.37

The composition of the total scattering cross section σ_{tot} considerably differs from that for He; σ_{el} for Ne continues to be appreciable on going to higher electron kinetic energies E, and indeed dominates over σ_{inel} up to 3000 eV, basically owing to the presence of the atomic inner core $1s^2 2s^2$. (On the basis of the Bethe theory one expects that σ_{inel} should dominate over σ_{el} at a sufficiently high E, owing to the behavior of the form $E^{-1} \ln E$, with relativistic modifications.) Yet the outermost subshell $2p^6$, containing six electrons, makes σ_{inel} appreciably larger than that for He.

2.2.2.6 Sodium

Sodium, Na, has been studied more extensively than Li, even though it is also difficult to prepare as atomic vapor. As a result, the data are probably more trustworthy than those for Li, but yet at a level far inferior to those for rare gases. Table 2.2.6 shows our adoption, based on Zecca et al. [96Zec1] and the recent literature cited there.

The general trend of the cross sections of Na is similar to those of Li, reflecting the structure $1s^2 2s^2 2p^6 3s$, containing one electron outside the inner core.

Table 2.2.6. Overview of cross sections for Na. Data are based primarily on Zecca et al. [96Zec1].

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
10	14	37	4.4	41	55
20	10	39	4.6	44	54
50	5	21	3.2	24	29
100	2.4	16	2.1	18	21
150	2.2	12	1.7	14	16

2.2.2.7 Argon

Eggarter [75Egg1, 80Egg1] critically reviewed data in view of criteria including the compatibility with the oscillator-strength spectrum, and produced a complete set of individual cross sections for inelastic scattering, with emphasis on high electron energies. de Heer, Jansen, and van der Kaay [79deH1] also critically examined data of a broader class including σ_{el}, and evaluated σ_{inel}. Upon evaluating σ_{inel}, they determined specifically the counting ionization cross section σ_i; multiple ionization amounts to 7 % or higher at electron kinetic energies above 200 eV. Hayashi [81Hay1] also presented recommended values. Table 2.2.7, prepared after consideration of these compilations, represents our adoption. The quality of the data should be good in view of many tests of criteria, including the compatibility of directly measured stot with the summation of individual cross sections, except at electron kinetic energies below 100 eV, and the consistency of inelastic-scattering cross sections with the oscillator-strength spectrum, and other theoretical constraints [75Egg1]. Uncertainties of cross-section values at 100 eV and below even for this repeatedly studied case represent a major challenge for future work.

The dominant component of σ_{tot} is σ_{el} throughout the energy range, up to 3000 eV, for which the data are shown, because of the presence of the substantial atomic inner core $1s^2 2s^2 2p^6$. At the same time σ_{inel} has an appreciable magnitude, indeed much greater than that for Ne, chiefly attributable to the sizable outer shell $3s^2 3p^6$.

Table 2.2.7. Overview of cross sections for Ar. Data are based primarily on de Heer et al. [79deH1] and Zecca et al. [96Zec1].

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
5	9				9
10	19				19
15	23				23
20	19	0.5	0.6	1.1	20
30	13	0.7	1.8	2.5	15
40	9.5	0.8	2.3	3.1	13
50	7.2	0.7	2.4	3.1	10
100	4.8	0.7	2.50	3.2	8.0
150	3.8	0.65	2.35	3.00	6.8
200	3.2	0.54	2.25	2.78	6.0
300	2.5	0.41	1.83	2.24	4.7
400	2.1	0.33	1.55	1.88	4.0
500	2.0	0.28	1.35	1.63	3.6
800	1.4	0.20	0.91	1.11	2.6
1000	1.3	0.17	0.79	0.96	2.2
2000	0.80	0.09	0.45	0.54	1.35
3000	0.57	0.055	0.35	0.40	0.97

2.2.2.8 Krypton

Table 2.2.8. Overview of cross sections for Kr. Data are based primarily on de Heer et al. [79deH1] and Zecca et al. [96Zec1].

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
5	15				15
10	13				13
20	20	1.3	1.2	2.5	23
30	13	0.9	2.6	3.5	17
40	11	1.0	3.2	4.2	15
50	9	0.98	3.4	4.4	13
100	5.9	0.88	3.4	4.3	10.2
150	4.5	0.76	3.2	4.0	8.5
200	3.7	0.62	3.1	3.7	7.5
300	3.2	0.48	2.4	2.9	6.1
400	2.8	0.40	2.1	2.5	5.3
500	2.4	0.33	1.8	2.2	4.6
1000	1.8	0.20	1.2	1.4	3.2
2000	1.1	0.11	0.67	0.79	1.9
3000	0.98	0.08	0.47	0.55	1.5

Table 2.2.8 represents our adoption primarily based on the surveys by de Heer et al. [79deH1] and by Zecca et al. [96Zec1]. The degree of compatibility of directly measured σ_{tot} with the summation of individual cross sections is comparable with the data for Ar.

The composition of σ_{tot} shows a feature different from that for Ar. Over a wide range, 150-1000 eV, σ_{el} and σ_{inel} contribute comparably to σ_{tot}. The greater importance of σ_{inel} than in Ar is understandable from the outer subshells $3d^{10}4s^{2}4p^{6}$, which give rise to successively greater contributions to inelasticity with the opening of many excitation channels at higher and higher E. Yet at 2000 eV and 3000 eV, σ_{el} remains to dominate, as that for Ar.

2.2.2.9 Xenon

Table 2.2.9 shows our adoption primarily based on de Heer et al. [79deH1] and Zecca et al. [96Zec1]. The degree of compatibility of directly measured σ_{tot} with the summation of individual cross sections is more modest than for the data for Ar.

The composition of σ_{tot} is roughly similar to that for Kr. However, as Zecca et al. [96Zec1] point out, the trend of σ_{inel} as a function of the electron kinetic energy E is more complicated upon closer examination (not readily discernible in Table 2.2.8 because of the coarse grid for E).

Table 2.2.9. Overview of cross sections for Xe. Data are based primarily on de Heer et al. [79deH1] and Zecca et al. [96Zec1].

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_{i}	σ_{inel}	σ_{tot}
5	34				34
10	38	0.2		0.2	38
15	38	0.2	1.0	1.2	39
20	29	3.7	2.5	6.2	35
30	13	3.8	4.2	8.0	21
40	9.6	2.9	4.6	7.5	17
50	8.8	2.4	4.8	7.2	16
60	6.3	2.1	4.9	7.0	13
80	6.2	1.7	5.0	6.7	13
100	5.5	1.4	5.0	6.4	12
150	4.4	0.9	4.6	5.5	10
200	4.9	0.8	4.0	4.8	9.6
300	3.8	0.6	2.9	3.5	7.3
400	4.0	0.47	2.86	3.3	7.3
500	3.5	0.40	2.53	2.93	6.4
700	2.8	0.30	2.01	2.31	5.1
1000	2.5	0.23	1.50	1.73	4.2
2000	1.7	0.13	0.91	1.04	2.7
3000	1.44	0.095	0.63	0.73	2.17

2.2.2.10 Mercury

Unlike Li and Na, mercury, Hg, has an appreciable vapor pressure even at room temperature. Therefore, it has been an object of extensive studies with respect to electron scattering since the celebrated experiment by Franck and Hertz [14Fra1], who demonstrated the presence of discrete energy levels through observation of electron transmission through mercury vapor. As a consequence, the electron-scattering cross sections of Hg are reasonably well established up to about 300 eV. Table 2.2.10 shows our adoption, which is based on the survey by Zecca et al. [96Zec1] and the recent literature cited therein.

The composition of σ_{tot} is roughly similar to that for Xe, but is more complicated in detail, and depending on the electron kinetic energy. This is attributable to the presence of as many as 80 electrons, the large dipole polarizability (which makes σ_{el} sizable), the outer electronic structure $4f^{14}5d^{10}6s^2$, which includes 2 valence electrons moving outside a not very rigid inner core.

Table 2.2.10. Overview of cross sections for Hg. Data are based primarily on Zecca et al. [96Zec1].

Energy [eV]	Cross sections [10^{-16} cm^2]				
	σ_{el}	σ_{ex}	σ_i	σ_{inel}	σ_{tot}
15	12	5	1.8	7	19
25	10	7	4.4	11	20
50	10	6	5.8	12	22
100	9	3.6	5.0	8.6	18
150	8	2.0	4.2	6.2	14
300	5	1.3	3.1	4.4	9

2.2.3 Additional remarks

For the other atoms in general, data found in the current literature are uncertain at least to the same level as those for the atoms explicitly discussed above. The survey by Zecca et al. [96Zec1] mentions to some data on Mn, K, Rb, Cs, Mg, Cu, Bi, and Pb, but not to the other some 80 atoms.

If the reader needs some values for an application, he may refer to some of the theoretical results. For instance, Inokuti et al. [81Ino1] give values of σ_{inel} for all atoms up to strontium (Z = 38), evaluated with the Bethe theory and thus applicable to sufficiently high electron kinetic energies.

2.3 Elastic scattering cross section

2.3.1 Generalities

Modern quantitative study of elastic scattering of electrons by atoms was pioneered by Westin [46Wes1], who systematized data with the use of the partial-wave analysis, as explained in many textbooks, for instance, [86Beth1] and [95Bur1]. To the extent that one may describe electron-atom interactions in terms of a central (i.e., spherically symmetric) potential, the elastic scattering is fully characterized by the phase shift, which is a function of the kinetic energy and the angular momentum of the electron, and may be readily evaluated for a given potential or may be determined to through a fit of measured data for the differential cross section. A key point of this analysis is that each partial wave, corresponding to a fixed angular momentum, is determined independently of the other partial waves. At sufficiently low energies, only a modest number of lower partial waves have appreciable values of the phase shifts, because higher partial waves cannot penetrate the inner region of the atom owing to the centrifugal potential. The partial-wave analysis is fully justified for electron kinetic energies below the lowest electronic-excitation threshold. (As a qualification, considerations of the electron spin necessitates a more elaborate treatment.)

The use of a central potential is an approximation when the electron kinetic energy exceeds the lowest electronic-excitation threshold for any atom, because any inelasticity means a loss of electron flux from the elastic channel and should affect the elastic-scattering cross section. Influence of inelastic scattering on elastic scattering can be formally incorporated by use of a complex-valued potential, as discussed by Burke and Joachain [95Bur1]. More importantly, when the target atom has an open electronic structure, the central-potential approach is a schematization in general. Nevertheless, the phase-shift data evaluated with a central potential are useful for estimating elastic-scattering cross sections when no other data source is available, and also for interpreting their systematics. (Further discussion on this topic is given in Subsection 2.3.3 below.)

It is customary to consider a central potential as consisting of several contributions. First, an electrostatic potential is produced by the nuclear charge Ze and the charge distribution of atomic electrons in the ground state, and is usually the dominant contribution. This potential approaches that of the bare nuclear charge, $-Ze^2/r$, at short distances r from the nucleus, and progressively weakens by the shielding by atomic electrons at larger distances, and eventually falls off exponentially at very large distances. Second, the electric polarization of the charge distribution of atomic electrons by a slowly approaching electron gives rise to a polarization potential, which behaves as $-\alpha e^4/(2r^4)$ at very large distances, where α represents the dipole polarizability of the atom. As the electron becomes faster, the electric polarization becomes less, and the polarization potential diminishes. Third, effects of the indistinguishability of the approaching electron from atomic electrons may be approximately represented by a potential, which is appreciable at distances comparable to the atomic size and shorter. (These effects are often referred to as electron-exchange effects. The term "exchange" historically originates from a presumed labeling of interacting electrons, which is in principle impossible, and is unfortunate, but is now too well established to be purged.) In general, a short-range part of a central potential primarily affects large-angle scattering, and a long-range part small-angle scattering; however, there is often an interplay of different parts of the potential, which defies straightforward interpretation.

If the potential for a particular partial wave, viz., the central potential plus the centrifugal potential has a sufficiently deep minimum at some distance, an incoming electron of a certain kinetic energy can be temporarily trapped, and stay near the atom for a period much longer than the ordinary transit time r_a/v before eventually leaving away, where r_a is the atomic radius and v is the electron speed. This phenomenon is called a (shape) resonance, and manifests itself as an abrupt change of the phase shift for the partial wave at the particular electron energy, Sometimes it leads to a drastic change in the differential cross section, or even in the (integrated) cross section near that particular electron energy.

2.3.2 Individual atoms

Many of the remarks made in Subsection 2.2.2 pertain to the total elastic-scattering cross section, and its relation with other cross sections, for each atom treated.

2.3.2.1 Hydrogen

Trajmar and Kanik [95Tra1] thoroughly reviewed theoretical and experimental data. One finds excellent agreement among recent results as well as consensus among recent recommendations. See Fig. 2.2.1 and Table 2.2.1.

2.3.2.2 Helium

Trajmar and Kanik [95Tra1] and Zecca et al. [96Zec1] reviewed extensive data, both theoretical and experimental. We adopt here the recommendation of [95Tra1] (Fig. 2.2.2 and Table 2.2.2). A resonance at 19.3 eV is most conspicuous in σ_{el}.

2.3.2.3 Lithium

As the survey by Zecca et al. [96Zec1] indicates, source data are limited in both scope and volume. See Table 2.2.3.

2.3.2.4 Oxygen

Itikawa and Ichimura [90Iti1], as well as Laher and Gilmore [90Lah1], reviewed data, Later Itikawa [94Iti1] present additional discussion. See Table 2.2.4, and also Fig. 2.2.3, taken from Itikawa [94Iti1].

2.3.2.5 Neon

Data up to 1978 were reviewed by de Heer et al. [79deH1]. More recent data were reviewed by Zecca et al. [96Zec1]. See Table 2.2.5. Values of σ_{el} are well established, to precision of a few percent. The total elastic-scattering cross section σ_{el} has a very broad maximum around 20…30 eV. Resonances at 16.11 eV and 16.30 eV are prominent in σ_{el}.

2.3.2.6 Sodium

Table 2.2.6 gives our adoption primarily based on the survey by Zecca et al. [96Zec1].

2.3.2.7 Argon

Data were reviewed by de Heer et al. [79deH1], and recently by Zecca et al. [96Zec1]. See Table 2.2.7. Values of σ_{el} are established, to precision of a few percent. There is a fairly sharp maximum around 16 eV. Resonances at 11.1 eV and 11.3 eV are also notable in high-resolution data.

At 0.235 eV, σ_{el} shows a conspicuous minimum. called the Ramsauer-Townsend minimum, as discussed in greater detail in Section 2.5.

2.3.2.8 Krypton

Data were reviewed by de Heer et al. [79deH1], and recently by Zecca et al. [96Zec1]. See Table 2.2.8. Around 10 eV, σ_{el} shows a maximum. A Ramsauer-Townsend minimum occurs at 0.55 eV.

2.3.2.9 Xenon

Data were reviewed by de Heer et al. [79deH1], and recently by Zecca et al. [96Zec1]. See Table 2.2.9. Around 7-8 eV, σ_{el} shows a broad maximum. A Ramsauer-Townsend minimum occurs at 0.65 eV.

2.3.2.10 Mercury

See Table 2.2.10.

2.3.3 Additional remarks

When no reliable experimental results are available for an application, one may wish to use theoretical results on electron elastic scattering by atoms. Recent sources of theoretical results for many atoms include Salvat et al. [85Sal1], Tilinin [88Til1], Browning [91Bro1], and Mayol and Salvat [97May1]. Tilinin [88Til1] discusses the momentum-transfer cross section, and presents a scaling relation claimed to be applicable to electron kinetic energies of $3 \cdot 10^2$-$1 \cdot 10^4$ eV and to all atoms. Browning [91Bro1] presents an analytic expression for the total elastic-scattering cross section as a function of the electron kinetic energy E and the atomic number Z, which is based on a survey of calculations with the phase-shift method and is claimed to be useful for E = 1-100 keV. Mayol and Salvat [97May1] have recently carried out extensive calculations of the phase shift using the Dirac equation with a central potential, and present total and momentum-transfer cross sections for all neutral atoms up to uranium for $E = 10^2$-10^9 eV. (The use of the Dirac equation is essential at E appreciable compared with mc^2 = 511 keV or higher.)

Table 2.3.1 presents comparison of the values given by Mayol and Salvat and by Browning with the values of the total elastic-scattering cross section we adopted as realistic in Tables 2.2.1-10. The values by Mayol and Salvat are reasonably close to our adopted values in general, and very close for Hg and rare gases except for He. The sizable discrepancies for H, Li, and Na might be indicative of the extent of applicability of a central potential to the electron scattering by an open-shell atom. The analytic expression of Browning is a low-precision approximation for heavier atoms at best.

Table 2.3.1. Calculated values of the total elastic-scattering cross section. Values given by Mayol and Savat [97May1] are indicated by *MS*. Values computed from a fitting equation, Eq. (4) of Browning [91Bro1], are indicated by *Br*. They are compared here with the values we adopted as realistic, and are indicated by *Ad*.

Atom	Cross section [10^{-16}cm^2]									
	E = 100 eV		E = 500 eV		E = 1000 eV			E = 2000 eV		
	MS	Ad	MS	Ad	MS	Br	Ad	MS	Br	Ad
H	0.33	0.40	0.058	0.061	0.029	0.048	0.029	0.014	0.024	
He	0.55	0.65	0.092	0.086	0.044	0.12	0.042	0.022	0.061	0.021
Li	2.43	2.0	0.55		0.28	0.21		0.14	0.11	
O	2.54	2.6	0.90	0.88	0.54	0.71		0.31	0.38	
Ne	2.15	2.3	0.81	0.77	0.51	0.92	0.46	0.30	0.50	0.29
Na	3.68	2.4	1.33		0.81	1.01		0.48	0.56	
Ar	4.92	4.8	2.05	2.0	1.38	1.63	1.3	0.88	0.95	0.80
Kr	5.90	5.9	2.69	2.4	1.90	2.73	1.8	1.30	1.73	1.1
Xe	3.90	3.9	3.86	3.5	2.83	3.43	2.5	2.02	2.26	1.7
Hg	9.21	9.0	7.01		3.71	4.14		2.59	2.80	

2.4 Excitation

2.4.1 Generalities

The present section treats the cross section for the excitation of lower discrete excited states. The term "lower" here means more precisely the excitation of an electron from the valence shell (technically from the outermost subshell) of atoms. The inner-shell excitation of atoms by electron collisions is certainly a subject rich in basic physics involved and is important in certain applications, but is beyond the scope of the present Chapter.

The following brief summary of general characteristics of the discrete-excitation cross section should serve as a preliminary to the presentation of cross-section data.

2.4.1.1 Dipole allowed and forbidden transitions

An important result of the Bethe theory [30Bet1, 71Ino1, 86Bet1] concerns the dependence of the cross section σ_s for the discrete excitation to state s on the electron kinetic energy E. When the transition from the ground state to state s is dipole allowed, i.e., when it has a nonvanishing dipole oscillator strength f_s, then σ_s behaves as

$$\sigma_s = 4\pi\, a_0^2\, \mathrm{Ry}^2\, E^{-1}\, [(f_s/W_s) \ln E + B_s], \tag{1}$$

for sufficiently high (but nonrelativistic) E, more precisely, at E exceeding many multiples of the excitation energy W_s of state s measured from the ground state, where B_s is a parameter that depends on s, a_0 represents the Bohr radius, $\hbar^2/me^2$ = 0.05292 nm, and Ry the Rydberg energy, $me^4/(2\hbar^2)$ = 13.606 eV. This result arises from the dominance of the dipole interaction of a fast incident electron

passing at a large distance with atomic electrons, whose action on the atom is equivalent to that of the absorption of photons characterized by a broad energy spectrum, over other modes of interactions effective at shorter distances. Indeed, the contribution of the dipole interaction is represented by the term proportional to $(f_s/W_s)\, E^{-1} \ln E$. The other contributions are represented by the term proportional to E^{-1} at high E. (At relativistic E, i.e., at kinetic energies comparable to, or higher than, mc^2 = 511 keV, Eq. (1) needs to be modified, as fully explained in [71Ino1].)

The above observation leads to the idea of plotting the product $E\sigma_s$ against $\ln E$, as first pointed out by Fano [54Fan1]. One should then obtain a curve that approaches at sufficiently high E a straight line with a slope given by f_s/W_s, apart from a universal constant. (At relativistic E, it is appropriate to plot $\beta^2\sigma_s$ against $\ln(\beta^2/(1-\beta^2))-\beta^2$, where $\beta c = v$ is the speed of an incident electron, as explained in [71Ino1].) Incidentally, the product $E\sigma_s$, apart from a universal factor, is significant also in the theory of electron collisions at low energies, and is called in this context the collision strength [96Bur1].

For a dipole-forbidden transition, for which f_s vanishes by definition, the $E^{-1} \ln E$ term is missing in Eq. (1). The distinction between a dipole-allowed transition and a dipole-forbidden transition is crucial at high E; in other words, σ_s for a dipole-forbidden transition decreases much more rapidly than σ_s for a dipole-allowed transition. More importantly, this trend of the E-dependence generally persists at considerably lower kinetic energies, i.e., down to E comparable to only a few multiples of W_s.

Furthermore, one should note differences among different kinds of forbidden transitions. When a transition is dipole-forbidden by the spatial symmetry, for instance, when it is an s-s or s-d transition, the excitation cross section σ_s is usually appreciable at fairly high kinetic energies. In contrast, when a transition is more strongly forbidden, for instance, when it involves a change in the spin quantum number, the excitation cross section σ_s decreases with electron kinetic energy more rapidly, for atoms of lower atomic numbers.

All the above-described general characteristics of the discrete-excitation cross section are useful on judging the correctness of experimental data.

2.4.1.2 Collision strength

Suppose that an atom A initially in a state i is excited to a state j by collision of an electron with momentum $\hbar k_i$, and let us write the (integrated) cross section for this process as σ_{fi}. After the collision the electron will have momentum $\hbar k_f$, which can be readily computed from the conservation of the total energy of the electron plus the atom. Similarly, we may consider the de-excitation of the atom in the state j back to the state i by collision of an electron with momentum $\hbar k_f$, and write the (integrated) cross section for this process as σ_{if}. Symbolically we may write

$$e(\hbar k_i) + A_i \leftrightarrow e(\hbar k_f) + A_f. \tag{2}$$

Then, there is a relation, called the principle of detailed balancing,

$$\omega_i\, k_i^2\, \sigma_{fi} = \omega_f\, k_f^2\, \sigma_{if}\,, \tag{3}$$

where ω_i represents the statistical weight of the state i, and ω_f that of the state f. The quantity on either side of Eq. (3) is called the collision strength and is usually denoted by symbol Ω_{fi}; obviously it is symmetric with respect to the interchange of i and f. (See p. 538 of [96Dra1].)

The collision strength is dimensionless, and is more closely connected with basic elements of the quantum theory of scattering than the cross section. It is convenient for data presentation because its dependence on the electron kinetic energy is often mild, milder than the dependence of the corresponding cross section itself. In addition, the collision strength is the same quantity used in the Fano plot, apart from a constant factor.

2.4.1.3 Resonance

The discrete-excitation cross section is often a smooth function of the electron kinetic energy E for a broad range of E. Exceptions arise in certain ranges of E owing to a temporary formation of a combined state of an electron plus an atom, which persists for a period much longer than the period of ordinary orbital motion of an atomic electron (which is of the order of $\hbar^3/me^4 = 2.419 \cdot 10^{-17}$ s). Such a state is called a resonance [86Fan1, 95McC1, 95Bur1]. For a resonance to occur, an electron must have a certain energy and angular momentum. The occurrence of a resonance is often interpreted in terms of an unoccupied atomic orbital in the Hartree-Fock approximation. A resonance manifests itself often conspicuously in the differential cross section for elastic or inelastic scattering, and sometimes cause sharp variations of the (integrated) cross section as a function of E, which can be characterized by a set of parameters as fully explained in [86Fan1].

2.4.1.4 Threshold behavior

The behavior of the excitation cross section σ_s near the threshold W_s, i.e., at E slightly above W_s, is determined by the motion of the scattered electron, which has a minute kinetic energy and is governed by long-range interactions with the atom left behind [84Rau1, 86Fan1]. In the simplest case where long-range interactions are negligible, σ_s should behave as in $(E - W_s)^{l+1/2}$, where $E - W_s$ is the excess energy and l is the orbital angular momentum of the scattered electron; usually the contribution from $l = 0$ should dominate near the threshold. When long-range interactions are appreciable (as is the case for instance for atomic hydrogen left in any of its discrete excited states, which are degenerate and thus give rise to strong dipole interactions), the threshold behavior is more complicated.

2.4.1.5 Relation to the ionization cross section

At a fixed electron kinetic energy, the cross section for the excitation to higher discrete states should be connected with the cross section for ionization resulting in ejection of an electron with zero kinetic energy, because the final states of higher and higher discrete excitations should converge to the continuum state of zero kinetic energy [86Fan1]. Consider for instance a Rydberg series of states characterized by the principal quantum number n and the orbital angular-momentum quantum number l of a single electron moving around a closed-shell ion core. The energy E_{nl} of the state n, l measured from the relevant ionization threshold is $\mathrm{Ry}/(n - \mu_l)^2$, where Ry represents the Rydberg energy (13.606 eV) and μ_l is the quantum defect characteristic of the series. Let the cross section for the excitation of state n, l be $\sigma_{n,l}$. Then, the product $(2\mathrm{Ry})^{-1}(n - \mu_l)^3\sigma_{n,l}$ should approach in the limit of large n the cross section $\mathrm{d}\sigma_l/\mathrm{d}w$ for ionization resulting in the ejection of an electron with kinetic energy w and angular momentum number l, in the limit of w approaching zero. Notice that $\mathrm{d}\sigma_l/\mathrm{d}w$ represents the cross section per unit range of w; the factor $(2\mathrm{Ry})^{-1}\ (n - \mu_l)^3$ represents the density of states per unit range of the excitation energy in the discrete spectrum. This relation is useful for estimating the cross sections for higher excitations from data on lower excitations, or for testing consistency of data [73Kim1].

As a consequence of the above consideration, one expects that $\sigma_{n,l}$ at a fixed electron kinetic energy can be fitted to the form $K_1/n^3 + K_2/n^4 + K_3/n^5 + \ldots$, K_1, K_2, K_3 ... being constant, which is often used in practice.

2.4.1.6 Photo-emission cross section

It is important to distinguish the discrete-excitation cross section from the cross section for the emission of photons corresponding to a particular spectral line. (The latter cross section is often referred to as the optical-excitation cross section when it is presented in an absolute value, and as the optical-excitation function when relative values are presented as a function of the electron kinetic energy.)

Suppose one considers a state s that emits a photon of interest. However, the state s in general may emit also a photon of different energy or may decay nonradiatively (e.g., by thermal collision with another atom or molecule, or by an Auger effect). Therefore, the probability of emission of a photon of interest (often called the branching ratio) is less than unity in general. Furthermore, the state s may be formed either directly by electron collision or indirectly by the excitation of a higher discrete state s' followed by a radiative or nonradiative transition, or even by a succession of such transitions; this indirect process is called a cascade.

The light emitted by an atom after electron collision is in general polarized and has an angular distribution. Thus, a quantitative treatment must account for the polarization and the angular distribution.

An extensive review of the topic up to 1988 is given by Heddle and Gallagher [89Hed1], and a survey of data by van der Burgt et al. [89van1]. A more recent review is given by Filippelli et al. [94Fil1].

2.4.2 Individual atoms

Subsection 2.2.2 presents adopted values of the total discrete-excitation cross sections for ten atoms. Many of the remarks given there are basic to discrete excitation in general. Following are additional discussions on selected data and topics.

2.4.2.1 Hydrogen

Janev and Smith [93Jan1] present recommended cross sections for the excitation to the 2s, 2p, 3s, 3p, and 3d states individually for the electron kinetic energy E up to 10 keV, with estimated accuracy of 10 % or better at E > 100 eV, and more modest at lower E. They also give the sum of the excitation cross sections for to n = 4 and n =5 states. See Tables 2.4.1-6. More recent recommendations for the 2s and 2p excitations by Trajmar and Kanik [95Tra1] are similar.

More significantly, the recent measurements by James et al. [97Jam1] of the 2p excitation cross section agree with the recent calculations with the convergent close-coupling method within 7 % for the electron kinetic energy from 14 eV to 1.8 keV. These authors carried out not only elaborate measurements, but also conducted extremely detailed evaluation of errors and a critical analysis of results in comparison with theory. An element of the analysis is the Fano plot, reproduced here as Fig. 2.4.1.

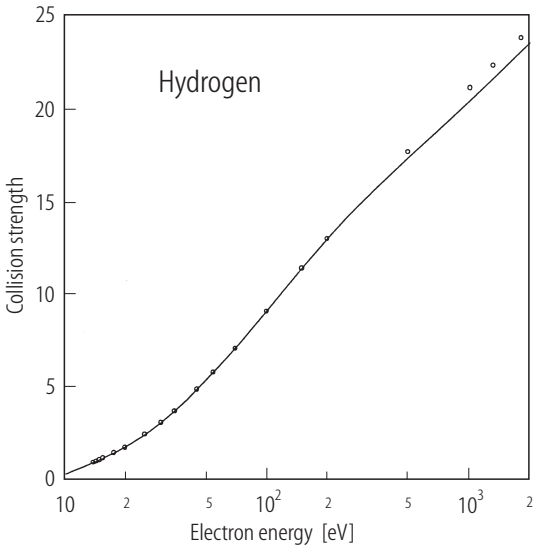

Fig 2.4.1 The Fano plot for the cross section for the 2p excitation of H, reproduced with permission from [97Jam1]. The vertical axis represents the collision strength, which is defined as $\omega_i(E/\mathrm{Ry})(\sigma_n/\pi a_0^2)$, where ω_i is the statistical weight of the initial state, E/Ry is the electron kinetic energy measured in units of the Rydberg energy, and $\sigma_n/\pi a_0^2$ is the cross section measured in $\pi a_0^2 = 0.280 \cdot 10^{-16}$ cm^2. (See p. 538 of [96Dra1].) The horizontal axis represents E on a logarithmic scale. The Bethe theory tells that the plot should approach a straight line at high enough E, as seen from Eq. (1).

Table 2.4.1. Cross sections for discrete excitations to the 2s and 2p states of H, as recommended by Janev and Smith.

E [eV]	σ [10^{-18}cm^2]	
	2s	2p
10.2	11.4	14.1
20	8.46	44.9
40	6.73	64.4
60	5.46	64.6
80	4.57	60.5
100	3.92	55.9
200	2.27	39.2
400	1.22	24.8
600	0.838	18.5
800	0.637	14.9
1000	0.513	12.5
2000	0.261	7.22
4000	0.131	4.08
6000	0.0879	2.90
8000	0.0660	2.27
10000	0.0528	1.88

Table 2.4.2. Cross sections for discrete excitations to the n = 2 states of H, as recommended by Janev and Smith.

E [eV]	σ [10^{-18}cm^2]
	n = 2
10.2	25.5
20	53.3
40	71.2
60	70.1
80	65.1
100	60.0
200	41.5
400	26.1
600	19.4
800	15.5
1000	13.1
2000	7.5
4000	4.22
6000	3.00
8000	2.35
10000	1.94

Table 2.4.3. Cross sections for discrete excitations to the 3s, 3p and 3d states of H, as recommended by Janev and Smith.

E [eV]	σ [10^{-18}cm^2]		
	3s	3p	3d
12.4	2.25	5.71	2.92
20	3.12	9.91	4.58
40	1.04	12.4	2.42
60	0.893	11.7	1.58
80	0.799	10.7	1.17
100	0.712	9.68	0.923
200	0.441	6.55	0.432
400	0.244	4.08	0.206
600	0.168	3.03	0.134
800	0.127	2.44	0.100
1000	0.103	2.05	0.0812
2000	0.0517	1.19	0.0412
4000	0.0258	0.676	0.0204
6000	0.0172	0.479	0.0136
8000	0.0129	0.375	0.0102
10000	0.0103	0.310	0.00822

Table 2.4.4. Cross sections for discrete excitations to the n = 3 states of H, as recommended by Janev and Smith.

E [eV]	σ [10^{-18}cm^2]
12.4	10.8
20	17.9
40	15.8
60	14.3
80	12.7
100	11.3
200	7.42
400	4.55
600	3.34
800	2.67
1000	2.23
2000	1.27
4000	0.718
6000	0.512
8000	0.398
10000	0.331

Table 2.4.5. Cross sections for discrete excitations to the n = 4 states of H, as recommended by Janev and Smith.

E [eV]	σ [10^{-18}cm^2]
14	7.02
20	9.44
40	7.46
60	5.98
80	5.03
100	4.37
200	2.72
400	1.62
600	1.17
800	0.936
1000	0.783
2000	0.441
4000	0.246
6000	0.173
8000	0.135
10000	0.111

Table 2.4.6. Cross sections for discrete excitations to the n = 5 states of H, as recommended by Janev and Smith.

E [eV]	σ [10^{-18}cm^2]
14	4.62
20	5.99
40	4.36
60	3.21
80	2.58
100	2.20
200	1.33
400	0.777
600	0.569
800	0.456
1000	0.379
2000	0.212
4000	0.119
6000	0.0837
8000	0.0652
10000	0.0537

2.4.2.2 Helium

de Heer et al. [92deH1] present recommended cross-section values for the excitation to the n^1S ($n = 2…6$), n^1P ($n = 2…6$), and n^1D ($n = 3…6$) states, as well as to the n^3S ($n = 2…6$), n^3P ($n = 2…6$), and n^3D ($n = 3…6$) states, for the electron kinetic energy up to 2 keV. Kato and Janev [92Kat1] gave analytic representation of the cross-section values recommended by de Heer et al. [92deH1].

A recent update by de Heer [98deH1] indicates that the recommended values are accurate to better than 10 % for the singlet excitations as well as the 2^3S and 2^3P excitations, but are less certain for the other triplet excitations. Tables 2.4.7-14 present the results of this update [98deH1], which should be even more accurate.

Table 2.4.7. Cross sections for discrete excitations to the 2^1S and 2^1P states of He, as recommended by de Heer.

E [eV]	σ [10^{-18}cm^2]	
	2^1S	2^1P
25	2.31	2.11
26.5	2.34	2.64
30.0	2.25	3.75
33.882	2.18	
35.160	2.15	5.41
40.0	2.07	6.43
45.0	1.95	7.71
50.0	1.85	8.21
60.0	1.70	9.51
80.0	1.42	10.14
100	1.30	10.10
150		9.17
200	0.794	8.31
250		7.61
300		6.94
350		6.39
400		5.95
500	0.380	5.67
600		5.02
800		3.75
900	0.238	
1000		3.13
1500		2.34
2000		1.85

Table 2.4.9. Cross sections for discrete excitations to the 4^1S and 4^1P states of He, as recommended by de Heer.

E [eV]	σ [10^{-18}cm^2]	
	4^1S	4^1P
25	0.129	0.170
26.5	0.114	0.201
30	0.162	0.310
35	0.165	
40	0.152	0.586
45	0.143	
50	0.133	0.833
60	0.113	0.943
80	0.0951	1.150
100	0.0906	1.069
150	0.0699	1.021
200	0.0592	0.891
250	0.0522	
300	0.0451	0.722
350	0.0403	
400	0.0362	0.613
500	0.0326	0.529
600	0.0263	0.476
800	0.0226	0.378
1000	0.0176	0.319
1500	0.0118	0.232
2000	0.00903	0.190

Table 2.4.8. Cross sections for discrete excitations to the 3^1S, 3^1P, and 3^1D states of He, as recommended by de Heer.

E [eV]	σ [10^{-18}cm^2]		
	3^1S	3^1P	3^1D
25	0.364	0.377	0.192
26.5	0.405	0.454	
30	0.437	0.738	0.228
35		1.11	0.248
35.16	0.413		
40	0.378	1.38	0.259
45		1.66	0.264
50	0.337	1.84	0.261
60		2.15	0.227
80	0.260	2.42	0.185
100	0.233	2.44	0.144
150	0.172	2.26	0.0933
200	0.146	2.08	0.0706
250	0.131	1.88	0.0579
300	0.119	1.77	0.0447
350	0.103	1.63	
400	0.0915	1.51	0.0320
500	0.0845	1.29	0.0242
600	0.0676	1.11	0.0199
800	0.0571	0.915	0.0156
1000	0.0463	0.793	0.0124
1500	0.0314	0.588	0.00780
2000	0.0245	0.468	0.00582

Table 2.4.10. Cross sections for discrete excitations to the 4^1D, and 4^1F states of He, as recommended by de Heer.

E [eV]	σ [10^{-18}cm^2]		E [eV]	σ [10^{-18}cm^2]	
	4^1D	4^1F		4^1D	4^1F
23.45		0.0158	150	0.0514	
25	0.105	0.0163	200	0.0388	0.000368
26.5		0.0158	250	0.0318	
30	0.122	0.0105	300	0.0246	
35	0.133		400	0.0176	
35.16		0.00889	500	0.0133	0.000105
40	0.139	0.00740	600	0.0110	
45	0.139		800	0.00855	
50	0.138	0.00513	900		0.0000564
60	0.120		1000	0.00685	
80	0.0984	0.00206	1500	0.00429	
100	0.0791	0.00136	2000	0.00320	

Table 2.4.11. Cross sections for discrete excitations to the 2^3S and 2^3P states of He, as recommended by de Heer.

E [eV]	σ [10^{-18}cm^2]	
	2^3S	2^3P
25	2.64	2.26
26.5	2.35	2.30
30	1.96	2.19
35.16	1.52	1.96
40	1.12	1.63
50	0.754	1.11
80	0.245	0.370
100	0.150	0.194
200	0.0287	0.0244
500	0.00240	0.00145
900	0.000494	0.000231

Table 2.4.13. Cross sections for discrete excitations to the 4^3S and 4^3P states of He, as recommended by de Heer.

E [eV]	σ [10^{-18}cm^2]	
	4^3S	4^3P
25	0.224	0.168
26.5	0.259	0.225
30	0.224	0.206
35.16	0.156	0.192
40	0.121	0.170
50	0.0781	0.130
80	0.0212	0.0473
100	0.0126	0.0267
200	0.00235	0.00335
500	0.000195	0.000203
900	0.0000389	0.0000303

Table 2.4.12. Cross sections for discrete excitations to the 3^3S, 3^3P, and 3^3D states of He, as recommended by de Heer.

E [eV]	σ [10^{-18}cm^2]		
	3^3S	3^3P	3^3D
25	0.708	0.462	0.124
26.5	0.677	0.477	0.112
30	0.571	0.541	0.112
35			0.0860
35.16	0.414	0.495	0.0603
40	0.303	0.426	
50	0.194	0.318	0.0365
80	0.0553	0.112	0.00778
100	0.0325	0.0603	0.00355
200	0.00615	0.00757	0.000325
500	0.000510	0.000460	0.0000132
900	0.000107	0.0000733	0.00000198

2.4.2.3 Lithium

Wutte et al. [97Wut1] reviewed experimental and theoretical data, and presented analytic representation of the cross sections for the excitation of the 2p, 3s, 3p, and 3d states. See Tables 2.4.15 and 2.4.16.

Table 2.4.14. Cross sections for discrete excitations to the 4^3D and 4^3F states of He, as recommended by de Heer.

E [eV]	σ [10^{-18}cm^2]	
	4^3D	4^3F
25	0.0782	0.00884
26.5	0.0614	0.0104
30	0.0584	0.00746
35.16	0.0487	0.00368
40	0.0373	0.00219
50	0.0218	0.00101
80	0.00461	0.000137
100	0.00227	0.0000389
200	0.000191	0.00000197
500	0.00000756	0.0000000717
900	0.00000115	0.0000000117

Table 2.4.15. Cross section for discrete excitation to the 2^2P state of Li, as recommended by Wutte et al.

E [eV]	σ [10^{-15}cm^2]
1.848	0.002631
2	0.8183
3	2.973
4	3.663
6	4.265
8	4.371
10	4.281
20	3.415
30	2.773
40	2.339
60	1.798
80	1.473
100	1.255
200	0.7434
300	0.5400
400	0.4284
600	0.3074
800	0.2421
1000	0.2009

Table 2.4.16. Cross section for discrete excitations to the 3^2S, 3^2P and 3^2D states of Li, as recommended by Wutte et al.

E [eV]	σ [10^{-17}cm^2]		
	3^2S	3^2P	3^2D
3.373	2.248		
3.834		0.7729	
3.878			0.004137
4	30.95	10.6	3.163
6	20.28	16.86	32.15
8	17.09	13.35	34.16
10	15.52	10.77	33.13
20	10.55	5.378	22.86
30	7.787	3.609	16.28
40	6.134	2.731	12.46
60	4.289	1.852	8.385
80	3.291	1.409	6.290
100	2.669	1.141	5.023
200	1.371	0.5934	2.493
300	0.9218	0.4052	1.656
400	0.6944	0.3091	1.239
600	0.4649	0.2110	0.8241
800	0.3494	0.1610	0.6173
1000	0.2799	0.1304	0.4934

2.4.2.4 Other atoms

The current knowledge of discrete-excitation cross sections of other atoms is often fragmentary, incomplete, and uncertain in many respects, and is therefore unsuitable for a simple systematic presentation. Nevertheless, the total amount of data in the recent literature, though fragmentary, is considerable, as seen in Table 2.4.17. Some of the data in the cited literature should be useful for the reader in need of cross-section values. The coverage is limited to articles that report experimentally measured values, rather than theoretically calculated values, and were published in 1980-1997.

For a broader coverage of the current literature, including articles reporting theoretical results, see the International Bulletin on Atomic and Molecular Data for Fusion, published by the International Atomic Energy Agency (IAEA), or access http://www.iaea.org/programme/amdis/ on the Internet. In particular, the relevant papers published before 1980 are listed in CIAMDA (an index to the literature on atomic and molecular collision data relevant to fusion research) publised by IAEA in 1980.

Table 2.4.17 shows different degrees of research activities on different classes of atoms. Many measurements have been reported on rare gases, viz., Ne, Ar, Kr, and Xe. Therefore, it may be timely to conduct a comprehensive survey of data and to update in effect the classic work by de Heer et al. [79deH1], although the total discrete-excitation cross sections given by them should not be drastically revised.

It is gratifying to see a considerable number of new reports on O and N, i.e. the two most important atomic species relevant to many applications such as aeronomy and combustion. A comprehensive analysis of cross-section data for N, similar to the work on O by Itikawa and Ichimura [90Iti1] and by Laher and Gilmore [90Lah1], might be appropriate in the near future. For Na and Hg also, an appreciable number of measurements have been carried out.

On the rest of the atoms cited in Table 2.4.17 only a few measurements have been performed, and only by a few groups of workers. A principal reason for this is the need of very high temperatures to vaporize those atoms.

Table 2.4.17. Recent literature on the discrete-excitation cross sections of other atoms (by courtesy of Y. Itikawa). Following is a list of articles reporting experimental results on discrete-excitation cross sections of each atom, published since 1980. For articles reporting theoretical results, see the International Bulletin on Atomic and Molecular Data published by the International Atomic Energy Agency, or access the Internet at http://www.iaea.org/programme/amdis/.

Atom	References
B	81Kuc1
N	80Spe1, 91Doe1, 92Doe3, 96Yan1
O	85Shy1, 85Zip1, 86Doe1, 86Shy1, 86Shy2, 86Vau1, 86Zip1, 86Zip2, 87Gul1, 87Vau1, 88Ger1, 88Gul1, 88Gul2, 88Vau1, 89Doe1, 89Doe2, 89Tei1, 90Lah1, 92Doe1, 92Doe2, 92Wan1
Ne	81Zav1, 82Mie1, 84Reg1, 84Sha1, 84Shp1, 84Tac1, 85McC1, 85Phi1, 85Teu1, 85Zav1,86Zet1, 87Bog3, 87Kha1, 87Mas1, 87Sch1, 87Tac1, 91Mar1, 91Peu1, 92Kha1, 92Zhe1, 93Mit1, 94Kha1, 96Kan2, 97Jan1
Na	80Sri1, 81Phe1, 82Fol1, 84Jad1, 84Jit1, 85Ril1, 85Stu1, 86Teu1, 88Teu1, 90Han1, 90Jia1, 92Mar1, 92Mar2, 93Yin1
Mg	88Bru1, 94Hou1
Ar	81Chu1, 81Zav1, 83Fer1, 84Shp1, 85Mit1, 85Zav1, 86Mit2, 86Tac1, 87Bog1, 87Kha1, 87Mas1, 87Sch1, 88For1, 88Li1, 88Nis1, 90Aje1, 90Bog1, 91Mar1, 91Mor1, 92Bla1, 92Cor1, 92Kha1, 92Zhe1, 93Mit1, 93Zhe1, 94Kha1, 94Mit1, 94Wan2, 96Tsu1, 97Jan1
K	80Vus1, 93Par1

Atom	References
Ca	82Dob1, 95Kuc1
Ti	88Smi1, 96Smi1
V	82Mel2
Cr	82Mel1
Mn	81Mel1, 81Mel2, 95Smi2
Fe	83Kol2
Co	83Kol1, 83Kol3
Cu	82Kra1, 95Ism1
Zn	81Bog1
Ge	82Kol1
Kr	81Tra1, 81Zav1, 82Phi1, 84Shp1, 85Kin1, 86Mit1, 87Bog2, 87Kha1, 87Mas1, 87Sch1, 88Ham1, 90Mur1, 90Tak1, 91Mar1, 91Zec1, 93Mit1, 93Zhe1, 94Gou1, 94Kha1, 94Mit1, 97Jan1
Rb	84Vus1, 93Par1, 93Wei1
Sr	94Bey1
Y	84Kuc1
Zr	83Kuc1, 96Smi1
Mo	82Bog1, 95Smi2
Rh	92Kol1
Pd	89Kol1
Ag	83Kra1
Sn	86Kol1
Xe	84Shp1, 86Pen1, 86Ver1, 87Mas1, 87Sch1, 88Fil1, 88Ham1, 88Kor1, 90DeJ1, 91Peu1, 91Suz1, 91Zec1, 92Kha1, 94Est1, 94Kha1, 94Mit1, 96Kan1, 96Kha1, 96Kha2, 96LeC1, 96Suz1, 97Jan1
Ba	93Zet1, 94Li1, 94Li2, 94Wan1
Sm	95Smi1
Dy	92Vas1, 94Smi1
Ho	92Vas1
Tm	92Vas1
Hf	93Kuc1, 96Smi1
Ir	91Smi1
Au	81Sha1, 90Hol1
Hg	84Pos1, 85New1, 90Pei1, 90Pei2, 93Pan1, 94Mul1, 96Zub1
Tl	91Ges1
Pb	91Ges1
Bi	97Smi1

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