
Gordon H. Dunn

JILA, University of Colorado, Boulder, Colorado 80309-0440

Burgeoning numbers of sophisticated computations now produce the atomic data needed for modeling of astrophysical hot objects. Examples are the data from the Iron and Opacity Projects discussed in this volume. To verify that the computed data correspond satisfactorily to reality, some experimental benchmarks are necessary. In this paper we discuss experimental benchmarks for electron-ion collisions resulting in ionization, recombination and excitation. We give some examples of areas where close agreement is found but underscore some areas where there are outstanding issues. Three issues are highlighted: 1) interfering resonances can significantly alter cross sections for excitation, 2) ambient electric and magnetic fields affect dielectronic recombination in ways that are not yet totally rationalized, and 3) experimental radiative recombination rates at zero energy appear anomalously large.

1. Introduction

Organizers of this symposium requested that the author address "atomic experiment" to give an overview of this area to update symposium participants on the recent progress and outstanding problems." For the brief time of the symposium oral presentation and the short space for written exposition, the author found this topic impossibly broad and instead selected a relatively more narrow topic delineated in the title of this paper. Even with this narrowing, the presentation here will be brief and may seem cryptic. There is no pretense of giving a general review with complete references. Rather, attention will be given to providing a brief status report including "recent progress and outstanding problems." Three issues are particularly highlighted.

Before proceeding to discuss specific processes, however, it is worthwhile to consider a relatively global feature of electron-ion collisions resulting from the attractive Coulomb field. The presence of an infinite number of Rydberg states in this field results in a very prominent role of resonances in excitation, ionization and recombination (and elastic scattering as well, though that is not discussed here). The cartoon in Fig. 1 heuristically illustrates the process of dielectronic capture, leading to formation of the compound state $(A^*e)\nu$. Decay along different channels leads to the various processes noted.
Fig. 1 Cartoon illustrating the process of dielectronic capture. As the colliding particles $A^+ + e$ approach each other in a), the electron gains kinetic energy in the Coulomb field. If the electron starts at infinity with kinetic energy $\epsilon$ less than that needed to excite the bound electron state $j$, it gains the needed kinetic energy as it approaches in the Coulomb field. If it excites the bound electron to state $j$ as in b), the incident electron now does not have enough energy to escape again to infinity, but is bound with energy $\epsilon$, a process which can only happen if $\epsilon$ is resonant with the energy of a Rydberg level. The resultant complex $(A^+e)^+$ can decay via different channels as discussed in the text.

If the two electrons in Fig. 1b again exchange energy with one going back to state $i$, the other electron will leave with the same energy as before the collision, $\Delta E - \epsilon$, and resonant elastic scattering will have occurred. Suppose next that the two electrons exchange energy, but that the core electron instead of going back to state $i$, goes to state $f$. Now, the exiting electron leaves with energy $E = \Delta E - \epsilon - E_0$, and we are left with an excited ion $A^+(f)$. In this case, resonant excitation has occurred. If the core-excited electron is an inner shell electron, it is likely that there is enough energy in the complex that it is energetically possible for more than one electron to be ejected. In this case, the result is a more highly-charged ion than the original target ion, and one has resonant-excitation-double autoionization (REDA) or a higher order version such as resonant-excitation-triple autoionization (RETA), etc. Next, if the core electron radiates (for example, undergoing the transition $j \rightarrow f$). Then we are left with a once-less-charged ion with one electron in a Rydberg state. This is the familiar mechanism of dielectronic recombination or DR. Of course, these processes may all take place through non-resonant routes as well.

The goals of experiments have most often been to provide touch points to reality for theory, and this is most fully accomplished by measuring cross sections rather than rate coefficients. Thus, the primary experimental approach has been the use of colliding beams wherein a beam of electrons is made to collide with a beam of ions and an appropriate collision product is detected. Beams colliding at right angles, called crossed beams, has been used for studying all of the three processes of ionization, excitation and recombination. Today, merged beams wherein the beams are brought together traveling in the same direction is the most frequently used technique for recombination and excitation, while crossed beams remains the mainstay technique to investigate ionization. However, merged beams have been used for some ionization studies as well. Heavy ion storage rings have introduced a wonderful new dimension into the study of electron-ion collisions, since extraordinary energy resolution can be achieved. As we look into each respective collision process, only a little more will be mentioned about experimental techniques.
2. Ionization

Ionization occurs via a variety of mechanisms: direct knock-on collision with an outer-shell electron; direct ionization of an inner-shell electron; excitation of an inner-shell electron with subsequent stabilization via autoionization, a process called excitation-autoionization (EA); resonant capture (see Sec. 1) involving excitation of an inner-shell electron with subsequent double-autoionization, a process called resonant-excitation-double-autoionization (REDA); and a process related to the last called resonant-excitation-auto-double-ionization (READI). All of these processes have been observed and all except READI have been found on occasion to very substantially affect the cross section. Excellent recent reviews have been written by Müller [1], and older reviews [2] are also helpful. Compendia [3], [4] contain most of the data up to their dates of publication, and recommended cross sections are also given [3].

Reference to the reviews or compendia shows a great quantity of both experimental and theoretical data. Experimental data are sometimes limited by the fact that the target ions are electronically excited, but if the case is important enough even this limitation can be overcome by using an ion storage ring for the measurements, since ions can be stored for a long time before measurements begin, thus giving a chance for the ions to relax. Typically, ionization cross sections measured either in crossed beams or in the storage ring are accurate to within 10%. One can safely say that if any cross section from a ground state ion is important enough to a user, it can probably be measured without undue effort if the request is made. This would be applicable to single and multiple total ionization cross sections and would not necessarily apply to partial cross sections to select excited states of the product ion. Few cross sections of this latter nature have been measured, and very few cross sections have been measured for ionization from excited state target ions. Thus, these points lay out the challenge for possible future work.

The cross section for ionization of Na-like Fe (Fe$^{15+}$) is shown in Fig. 2. Most of the ionization mechanisms discussed can be seen in this figure. Both crossed beams [5] and storage

![Graph](image-url)

Fig. 2 Cross section for ionization of Fe$^{15+}$. Data are from Ref. 5, 6, and 7.
ring data [6] are presented and two theoretical calculations [6], [7] are shown as well. The simple Lotz formula represents the direct ionization cross section below 710 eV quite well. The theoretical calculations do an adequate - though not perfect - job of describing the cross section where EA and REDA play a large role. One might say that this figure broadly represents the present status of the capability of both experiment and theory; though crossed beams measurements are much more competitive with the ring measurements for lower charge state ions where the quality of the crossed beams data can be of similar quality to that shown in the figure for the ring data.

3. Excitation

Just as with ionization, excitation takes place through both direct knock-on collisions and via dielectronic capture as discussed in Sec. 1. Until the 1990's, total absolute cross sections were all measured using crossed beams of electrons and ions and resultant fluorescence was detected and measured. Using this method, accurate absolute cross sections were obtained for excitation of radiating states of a substantial number of singly-charged ions and a few multiply-charged ions.

The crossed beams work has been reviewed by Phaneuf [8]. A safe overview of the data using the crossed-beams-fluorescence technique is that general agreement with theory was the norm provided the theory was pushed far enough with adequate wave functions, proper phases, etc. In some instances, most notably the excitation of the Li-like ion, Be⁺, it took many years and many tries at theory to obtain agreement with the experiment [9] which was accepted by many as a benchmark. The most recent theory paper, which also describes earlier theoretical efforts as well, is reported by Pan [10], and this seems to largely overcome the 15% disagreement of earlier theory with experiment.

A large fraction of the fluorescence measurements were on resonance state excitations with Δτ = 1, Δs = 0. As noted, the agreement of theory with experiment in these cases was generally adequate. Resonances generally don't play a dominating role in such excitations, and little was learned from the fluorescence measurements about the adequacy of the theory to account for the role of resonances in excitation. Also, as noted, the measurements were largely on singly-charged ions, since the fluorescence technique is plagued by a detection sensitivity of about 10⁻⁴ - give or take a little, and beam-beam experiments produce low signal rates to start with. To make it possible to make measurements on multiply-charged ions and to make measurements on excitations which don't necessarily produce radiation, a new approach was developed [11], [12] called the merged-electron-ion-beams-energy-loss (MEIBEL) technique.

In this method electrons and ions are merged using crossed E and B fields. They then interact over a common path of some distance, and are separated in a second region of crossed E and B fields. Electrons having lost energy to an inelastic collision are separated from the main electron beam and led to impact upon a position-sensitive detector. Careful measurement of the beam currents, the beam geometry and overlaps of the beams, and the signal counts yields absolute cross sections for the inelastic process. In contrast to the fluorescence method, this technique has a detection sensitivity of nearly unity, and can make measurements for excitations to non-radiating states.

A main goal of these experiments has been to determine how well theory is doing when computing resonance excitation. To illustrate this, Fig. 3 [13], adapted from Ref. [14].
Fig. 3 Theoretical electron-impact excitation cross section versus center-of-mass interaction energy for the $3s^2 \, ^1S \rightarrow 3s3p \, ^3P^o$ transition in Ar$^{4+}$. The curve is adapted [13] from 8 state CCR results of Ref. [14].

shows the theoretical cross section for the $3s^2 \, ^1S \rightarrow 3s3p \, ^3P^o$ intercombination transition in the Mg-like ion Ar$^{4+}$. The minuscule step near 14.1 eV is the cross section for the direct excitation process which is seen to be tiny compared to the resonance contributions which start up shortly thereafter. There are a number of large resonance contributions in the next 2 eV interaction energy. This is not an extraordinary example. Resonances similar to these occur commonly, and may dominate as they do here. It is exceedingly important to do experiments which will show reality against which to test calculations such as this.

Figure 4 shows experimental measurements using the MEIBEL technique for the transition and energy range shown in Fig. 3. The bars in the figure represent uncertainties at a high confidence level (approximately 90% C.L., 1.7 $\sigma$). The experiment makes use of an electron beam with energy width of about 0.24 eV; so many of the detailed features of Fig. 3 are smeared out. For a sensible comparison, therefore, Fig. 4 also shows the convolution of the theoretical results with an 0.24 eV Gaussian energy distribution. The results strongly imply that there is

Fig. 4 Electron-impact excitation cross section versus center-of-mass energy for the $3s^2 \, ^1S \rightarrow 3s3p \, ^3P^o$ transition in Ar$^{4+}$. Points are measured [13]. The solid curve is a convolution of a Gaussian of width 0.24 eV FWHM with CCR results shown in Fig. 3. Resonance interference is inferred [13].
appreciable interference of the resonances between 14 and 15 eV, causing them to change relative magnitudes and leading to important disagreement of the theory with the experiment in this region. This is distinct from the energy range 15 - 16 eV; though even here there seems to be some difference between the experiment and the convoluted theory.

Griffin et al [15] had made the point that there is extreme sensitivity of some resonances to the exact energies of the resonances and caution should be exercised in using theoretical results with such resonances. In an effort to rationalize the theory and experiment, Griffin et al [16] found that moving the location of the resonances in Ar" had little effect on the convoluted result between 15 - 16 eV; however, they found a very large effect when the resonances between 14 -15 eV were moved. Previous experimental results [17] using MEIBEL for Kr" showed similar interference and strong sensitivity to moving [18] of the resonances.

**ISSUE #1.** Though theory has been developed to the point that enormous numbers of resonance contributions to excitation are calculated, there is strong experimental and theoretical evidence that the results are not typically accurate enough to account for the resonance interference that may occur among resonances. Resonance interference may materially affect the cross section. More work is required.

4. Recombination

The "direct" photo-recombination mechanism for atomic ions and electrons may be considered to be "simple" radiative recombination (RR) wherein an electron in passing an ion gets captured into some bound state of the atomic ion by radiating the excess energy away. It is the inverse process of photoionization, and the mechanism has long been considered to be well-understood [19], despite the fact that it was not until recently that the process was first directly measured experimentally. Theoretical RR rates have been expansively used "everywhere" from calculations involving the formation of the universe to laboratory plasmas. Now there arises a puzzle: newly measured laboratory RR rates often do not agree with theoretical rates at very low velocities.

Heavy ion storage rings have provided a means to study this process. With these devices, heavy ions of select charge are stored in a ring for long times. On successive turns, they encounter an electron target called the "electron cooler" where through Coulomb collisions the ion velocity becomes the same as the electrons. Hereby, one can achieve very low relative velocities and very narrow relative velocity resolution. By detecting once-less-charged particle fluxes, accounting for primary fluxes, interaction paths, etc. one can deduce the recombination rate. By varying the electron velocity from the "cooling" value, one can obtain rates as a function of relative energy.

Though first measurements using these and related merged beams gave rates that pretty much agreed with theory, it was not long before staggering surprises were found. Rates were found which were as much as several tens of times greater than predicted by theory. Hypotheses including three-body effects, dielectronic recombination interferences, and others have been put forth and examined in a large literature that has grown up over only a few years time and which cannot be fairly or adequately referenced here; so we give only a sample. Müller et al [20] give a good summary of some of their findings for complex heavy ions which have shown "zero" energy RR rates as high as $1.8 \times 10^4$ cm$^3$s$^{-1}$. It seems likely that in some of these cases dielectronic recombination (DR) resonances may accidentally be located at zero energy and have strong interference with RR. However, in cases where there are no likely resonances there, enhancement of the rates to values above those predicted by theory is often present. This is
nowhere more clearly emphasized than in the case of bare ions where there are no DR resonances and where "enhancements" of several times have been observed at "zero" energy. A recent report on some of this work, including references to work by others, is given by Gao et al [21]. So far no fully consistent hypotheses have been set forth which resolve these anomalies and work continues to find answers.

**Issue #2. High resolution measurements at "zero" relative energy yield photo-recombination rates which are substantially higher than predicted by theory, ranging from a few times higher for bare ions to several tens of times higher for more complex ions. No fully consistent hypotheses have resolved the issues.**

The resonant form of photo-recombination or DR has also been beset with enhancement issues starting from the time of the first direct measurements on the process. All of the earliest measurements seemed to give cross sections larger than predicted by theory. The differences were then largely rationalized by invoking mixing of Rydberg states by ambient electric fields. Mixing of states with small autoionization rates (e.g. high ℓ) with those of high autoionization rates (e.g. low ℓ) effectively increases the counting of the states participating in the DR process, and thus increases the cross section. Systematic studies were then carried out [22] on Mg⁺ looking at specific high Rydberg states as a function of well-defined fields, and reasonable agreement with theory was found for this very dramatic dependence of DR cross section on electric field. At the time, not all the experiments [23] were brought equally into agreement with theory, but in those cases that were not, parameters were not well enough defined to carry the issue much further. Thus, little further attention was paid to the problem except by the group at Harvard who continued to better define experimental conditions for some of the early cases found to be in disagreement, specifically for the Li-like ion, C³⁺. That group continued to find [24] an indication of disagreement with theory, though they later did other calibrations of their apparatus and declared [25] that they did not think the disagreement was significant. Their careful work, however, was convincing enough that it was decided that something more must be done on the issue of field enhancement of DR.

The heavy ion storage ring CRYRING at Stockholm was used to study DRF (DR in fields) over the field range 0 to 183 V/cm. Results showing cross section versus relative energy [26] are reproduced in Fig. 5 for nine different values of the imposed electric field. The results very dramatically illustrate the field effect for high Rydberg levels corresponding to formation at energies 20 eV and up. The integrated collision strength from 20 eV to 25 eV versus electric field was compared (26) with theory of the type used to describe the Mg⁺ results [27], [28], and though the general magnitude of the field enhancement is in rough agreement, there is fairly large disagreement in the functional behavior.

Generally, the effect of all but very large magnetic fields on DRF was thought to be very small and was neglected. However with the above disparate results on Si¹⁺ combined with the less definitive disagreements from older experiments, Robicheaux and Pindzola [29] revisited the issue of whether or not magnetic fields would play a role. They made a model calculation which indicated that quite possibly the disagreements of the older experiments as well as those for Si¹⁺ could be attributed to not accounting for the simultaneous presence of a crossed magnetic field as well as an electric field. However, the detailed calculations for Si¹⁺ are dauntingly large even with modern computers; so an in-depth comparison could not be made. Furthermore, the B field in the experiment was not systematically varied with fixed E field with the intent of looking for this effect.

**Issue #3. New definitive experiments on DRF have again confirmed that this effect can be very large for moderate fields. The theory which was thought to explain these effects adequately has been called into question by the experiments. New theoretical models suggest that the presence of crossed electric and magnetic fields can affect DRF quite differently than**
Fig. 5 Reaction rate versus relative energy of electron and Si$^{11+}$ for DRF. Cross sections are given for nine different fields: 0.0, 9.2, 18.4, 32.0, 46.0, 68.8, 91.5, 137.5, and 183.1 V/cm. Data are from ref. 26.

electric fields only. A full theoretical calculation on a given system looks prohibitively large at this time. Further experiments with variation of more parameters are called for.

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References


