This Week's Citation Classic

Bates D R, Kingston A E & McWhirter R W P. Recombination between electrons and atomic ions. I. Optically thin plasmas. *Proc. Roy. Soc. London Ser. A* 267:297-312, 1962.

[Dept. Applied Mathematics, Queen's Univ. Belfast, Northern Ireland; Mathematical Inst., Univ. Liverpool; and Culham Lab., UK Atomic Energy Authority, Abingdon, Berkshire, England]

This is the first of a series of papers on electron-ion recombination in dense plasmas and on how some of the energy released by the recombination heats the plasma. In it a statistical theory describing the loss mechanism, for which the name *collisional-radiative recombination* is proposed, is developed. This theory enables the recombination coefficient α to be computed at a chosen temperature from the relevant spontaneous radiative transition probabilities and the rate coefficients for radiative recombination and collisional excitation and ionization. Detailed computations are carried out on α for an optically thin plasma in atomic hydrogen and also on α for an optically thin plasma in which electrons recombine with bare nuclei of charge Ze to form hydrogenic ions. [The *SCI*® indicates that this paper has been cited in over 590 publications.]

Collisional-Radiative Recombination

Sir David Bates
and
A.E. Kingston
Department of Applied Mathematics and
Theoretical Physics
Queen's University
Belfast BT7 1NN
Northern Ireland

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Around 30 years ago, there was a growing interest in dense plasmas that stemmed from the research being done on nuclear fusion. Information on the recombination coefficient was badly needed. Its calculation seemed complicated because in the course of recombining an electron follows one of an infinity of possible paths through various bound and free states. Fortunately the complication may be avoided. Considering an H - H^+ - e plasma for the sake of definiteness atoms enter and leave a particular excited state at rates much faster than the rate at which the number density of atoms in that state changes. It was readily possible to write down the set of linear equations that govern the steady state number densities of excited atoms for given number densities of free electrons and of ground state atoms. Having found the steady state number densities, it was a straightforward task to calculate the downward electron current and thus the recombination coefficient. The problem was ripe for solution in 1960-1961 for two reasons. First, the basic theoretical work on the required atomic properties had recently been done: thus tables of spontaneous radiative transition probabilities and radiative recombination coefficients had been published by L.C. Green, P.P. Rush, and C.D. Chandler[1] and by M.J. Seaton,[2] respectively, and simple but reasonably accurate formulae for the rate coefficient of binary electron-atom inelastic collisions had been given by M. Gryzinski.[3] Secondly, computers that enabled quite a large set of linear equations to be solved had recently become available.

The paper appears to be referenced mainly in connection with plasma physics research related to nuclear fusion (*cf.* M.F.A. Harrison[4]). It has become a *Citation Classic* because it is a convenient source of a rather cumbersome set of equations and because plasma physics has continued to be a very active field, and most scientists are punctilious in acknowledging relevant earlier work.

While it is gratifying to have written a paper that has been cited often, we recognize that the number of citations is not always a measure of the merit of an investigation. One of us (DRB) can be neutral in comparing the subject of this essay with a paper[5] with only three-tenths as many citations yet which gave the first correct theory of dissociative recombination, a process of great importance, and which was the more original of the two in that it displaced an authoritative but totally erroneous formulation of the problem. Its relative lack of citation success is probably partly because it is much too compactly written and does not contain a diagram that would have made the central idea accessible to nonmathematical readers and partly because dissociative recombination has not attracted many theorists. There is also a rum supplementary reason. While punctilious in the respect mentioned above, many scientists are content to take references from the work of others without checking their relevance. A mistaken reference in an influential early paper has had many descendants so that it has been a not uncommon practice to attribute the theory of dissociative recombination to DRB and H.S.W. Massey.[6] In fact, DRB and Massey did not even discuss the theory of dissociative recombination. Their paper is concerned with recombination in the Earth's ionosphere. Having over a number of years examined and eliminated all other loss processes they could conceive, they cautiously suggested that dissociative recombination is rapid and is the key process involved. However, they did not see how this could be so.

1. **Green L C, Rush P P & Chandler C D.** Oscillator strengths and matrix elements for the electric dipole moment for hydrogen. *Astrophys. J. Suppl. Ser.* 3:37-50, 1957. (Cited 145 times.)
2. **Seaton M J.** Radiative recombination of hydrogenic ions. *Mon. Notic. Roy. Astron. Soc.* 119:81-97, 1959. (Cited 315 times.)
3. **Gryzinski M.** Classical theory of electronic and ionic inelastic collisions. *Phys. Rev.* 115:374-83, 1959. (Cited 295 times.)
4. **Harrison M F A.** Atomic and molecular collisions in the plasma boundary. (Post D E & Behrisch R, eds.) *Plasmas of plasma-wall interaction in controlled fusion.* New York: Plenum Press, 1986. p. 281-350. (Cited 5 times.)
5. **Bates D R.** Dissociative recombination. *Phys. Rev.* 78:492-3, 1950. (Cited 175 times.)
6. **Bates D R & Massey H S W.** The basic reactions in the upper atmosphere. II. The theory of recombination in the ionized layers. *Proc. Roy. Soc. London Ser. A* 192:1-16, 1947. (Cited 105 times.)

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