Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Radiation Physics and Chemistry 75 (2006) 656–695
Radiation Physics and Chemistry
www.elsevier.com/locate/radphyschem

The pair-production channel in atomic processes

Ali Belkacem[a,*], Allan H. Sørensen[b]

[a]Lawrence Berkeley National Laboratory, Chemical Sciences, Mail Stop 2R0300, 1 Cyclotron Road, Berkeley, CA 94720, USA
[b]Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark

Received 2 April 2004; received in revised form 16 December 2004; accepted 1 March 2005

Abstract

Assisted by the creation of electron–positron pairs, new channels for ionization, excitation, and charge transfer open in atomic collisions when the energy is raised to relativistic values. At extreme energies these pair-production channels usually dominate the "traditional" contributions to cross sections that involve only "positive-energy" electrons. An extensive body of theoretical and experimental work has been performed over the last two decades to investigate charge-changing processes catalyzed by pair production in relativistic heavy ion collisions. We review some of these studies.

Keywords: Pair production; Atomic processes

1. Introduction

An atom, viewed in the simple Dirac picture, is a system that contains a finite number of electrons which occupy discrete positive-energy states and move on a background of an infinite number of electrons occupying all negative-energy states, the "Dirac sea". Since the early days of quantum mechanics atomic-collision studies have dealt mostly with the excitation, charge transfer, or ionization of the positive-energy electrons. Extensive studies of atomic processes in photon–atom, electron–atom, and ion–atom collisions have lead to a very good understanding of how such processes occur. By means of the theoretical and mathematical tools developed over the decades it is possible to predict cross sections quite accurately. At sufficiently high energies, the cross sections for ionization and excitation upon photon impact and charge transfer upon ion impact decrease with increasing collision energies. However, it was realized in the mid 1980s, that as the energy in the collision increases the negative-energy electrons will play a major role in atomic processes by opening new channels that involve pair creation. When pair production is taken into account, the cross section of atomic processes like photoionization and charge transfer reverses and starts to increase with increasing collision energies. Over the last two decades many studies have been published, both theoretical and experimental. The effort has largely been driven by the effect the increase in cross section has on the design and operation of high-energy accelerators.

In our contribution to the current Special Issue of Radiation Physics & Chemistry on pair production we focus on the pair-production channel in atomic processes and discuss how pair production affects well-known atomic processes such as charge transfer, ionization, excitation, and energy loss. However, the intent is not to provide an exhaustive review of all the

*Corresponding author. Tel.: +1 510 486 7778; fax: +1 510 486 7779.
E-mail address: abelkacem@lbl.gov (A. Belkacem).

0969-806X/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.radphyschem.2005.03.003

work done in this field. Instead we aim at introducing the physics and we shall follow the line of our own contributions to the field.

The article is divided into three major sections. Each section includes both theoretical and experimental work. Section 2 addresses atomic processes in photon–atom collisions. We discuss the various channels that lead to charge change, excitation, and ionization when a high-energy photon impinges on an atomic or ionic target.

Section 3 concerns ion–ion and ion–atom collisions. We make special emphasis of the importance of bound-free pair production in ion–ion collisions at energies that are routinely encountered in relativistic heavy-ion colliders. In part of the section we use the equivalent photon method which is often as accurate as much more involved methods at very high energies. The method links the photon impact section to the heavy-ion impact section. However in some cases perturbative methods like the virtual photon method break down as is evident from experimental findings. Hence we discuss non-perturbative treatments of ion–ion and ion–atom collisions as well. The very important role that pair production plays in the energy loss of a relativistic heavy ion penetrating matter is also discussed.

The third and shortest part, Section 4, departs a little from the two previous sections as it deals with coherent and resonant effects in pair creation as such when the target is a single crystal. We review briefly the work done on coherent pair production in the perturbation limit as well as the effect on the pair production of the strong transverse field which exists in crystals.

Natural units are used throughout our contribution ($\hbar = m = c = 1$; m is the electron mass except in cases involving the creation of heavier leptons, Sections 2.2.4 and 3.2.4). The Compton wavelength $\lambda_C = \hbar/mc$ is hence the unit of length and cross sections come out in units of λ_C^2 (1.4912 kb for electrons). In the section on photon impact, Section 2, the atomic number of the target is denoted simply by Z. In the section on heavy-ion impact, Section 3, the atomic number of at least one of the collision partners is always supplied with a subscript (p for the projectile, t for the target).

2. Photon impact

We begin our journey into the world of vacuum-assisted atomic transitions by considering photoprocesses. Since photons essentially are nothing but electromagnetic field pulses, it is obvious that photon interactions are basic to the understanding of atomic collisions in general. The Weizsäcker–Williams (WW) method of virtual quanta provides a direct demonstration of this. Two vacuum-assisted processes will be considered in this section. In Section 2.2 we discuss charge change of a bare ion mediated by photoconversion into a pair with the negatively charged particle produced directly in a bound state centered on the ion. This process, which we shall term bound-free pair production, has also been given the alternative name of capture from pair production. In Section 2.3 we discuss photoionization which is one of the most basic atomic collision processes and demonstrate how pair production plays a very crucial role at high energies. However, before turning to these two specific cases we shall provide a suitable background knowledge of what we may call the standard case of pair creation, namely production of pairs of free electrons and positrons upon photon impact on an atom; Section 2.1.

2.1. Production of free particles

The creation of free pairs upon photon impact on an atom is covered in many textbooks and reviews. Standard references are the classic books by Heitler (1954) and Jauch and Rohrlich (1980). Among the reviews that of Bethe and Ashkin (1953) may be mentioned as well as the introduction to the tabulation by Hubbell et al. (1980). See also the survey by Hubbell and Seltzer (2004) which includes references to recent work, as well other contributions to this Special Issue. For the sake of the discussion to follow we include a few central formulas and results.

Photoproduction of an electron–positron pair in the field of an atom involves the interaction of an electron with the radiation field as well as with the atom. The interaction with the radiation field is treated as a perturbation. The interaction with the atom will sometimes be treated exactly, but for the creation of unbound particles the standard treatment, which leads to the so-called Bethe–Heitler results, is a lowest order perturbation approximation for this interaction as well. In effect, pair creation is then a second-order (two-vertex) process. Correspondingly, the probability for a transition from an initial state O (negative-energy electron, incoming photon) to a final state F (electron excited to positive energy leaving a hole behind, recoiling atom) reads

$$P_{\mathrm{F|O}} = 2\pi \left| \sum_n \frac{H_{\mathrm{F}|n} H_{n|\mathrm{O}}}{E_{\mathrm{O}} - E_n} \right|^2 \rho_{\mathrm{F}}. \tag{1}$$

Here ρ_{F} is the density of final states and the sum in the compound matrix element is over all intermediate states (n runs through a complete set of states in principle, in praxis only a few contribute). In Eq. (1) one of the matrix elements of the Hamiltonian H corresponds to the absorption of the primary photon while the other corresponds to the scattering in the atomic field. Describing the electron in the various states by plane waves,

$$\psi = u e^{i\mathbf{p}\cdot\mathbf{r}}, \tag{2}$$