Radiative Electron Capture and the Photoelectric Effect in Hydrogen-like High-Z Systems

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Since the early days of quantum theory, the photoelectric effect has been a subject of continued interest. The first system to be treated theoretically, was the hydrogen atom. With the advent of heavy-ion accelerators and electron beam ion traps (EBIT) that are able to produce bare or hydrogenlike high-Z ions up to U^{92+}, new possibilities have been opened up to study the photoeffect in single-electron systems other than hydrogen. While high-Z hydrogen-like ions cannot easily be used as targets for the photoelectric effect, it is possible to study the inverse reaction, namely radiative recombination (RR) of free electrons with bare ions, either in a trap or for projectiles. This process plays an important role in plasma physics, in particular for the spectroscopic analysis of fusion plasmas. In accelerator experiments performed at the GSI, one observes radiative electron capture (REC) from low-Z target atoms, in which the loosely bound electrons can be considered as quasifree. Indeed, it turns out that for high-Z ions, the single-electron photoeffect is most efficiently studied by its inverse reaction, RR, which, to a very good approximation, is experimentally implemented as REC.

The differential cross section for ionizing a single electron from a shell n with angular momentum j_n by an unpolarized photon and using electron detectors insensitive to the spin of the emitted electron is given by [1, 2, 3]

$$\frac{d\sigma_{\rm ph}}{d\Omega} = \frac{\alpha\, m_e c^2}{4\,\hbar\omega}\,\frac{\lambda\!\!\!^{-}{}_{\rm c}^{\,2}}{2(2j_n+1)}\,\sum_{\mu_n}\sum_{m_s}\sum_{\lambda}|M_{\mathbf{p},n}(m_s,\lambda,\mu_n)|^2\,. \tag{1}$$

Here $\lambda\!\!\!^{-}{}_{\rm c}$ is the electron Compton wave length, and we have averaged over the $(2j_n+1)$ angular momentum projections μ_n in the bound state, over the circular polarizations $\lambda = \pm 1$ of the incoming photon and have summed over the spin components $m_s = \pm\frac{1}{2}$ of the emitted electron. The transition matrix element is

$$M_{\mathbf{p},n}(m_s,\lambda,\mu_n) = \int \psi^{\dagger}_{\mathbf{p},m_s}(\mathbf{r})\,\boldsymbol{\alpha}\cdot\hat{\mathbf{u}}_\lambda\, e^{i\mathbf{k}\cdot\mathbf{r}}\,\psi_{j_n,\mu_n}(\mathbf{r})\,{\rm d}^3r, \tag{2}$$

where $\boldsymbol{\alpha}$ represents the set of Dirac matrices, $\hat{\mathbf{u}}_\lambda$ is the unit vector of photon polarization, and $\mathbf{k}$ is the photon wave vector. The initial bound-state spinor wave function is characterized by a Dirac quantum number $\kappa_n = \pm(j_n+\frac{1}{2})$ and the angular momentum projection μ_n. The final continuum wave function describing the relativistic electron emitted with asymptotic momentum $\mathbf{p}$ and spin projection m_s is decomposed into partial waves.

We have calculated RR for capture into the K,L, and M shells of various projectiles yielding good agreement with experimental data [4]. In particular, we have shown that for K-REC at moderately relativistic energies of a few hundred MeV/u [5] the differential cross section *roughly* follows a $\sin^2\theta$ distribution including retardation, i.e., all multipoles. However, at forward angles the cross section has been predicted [2] to be finite owing to magnetic spin-flip transitions. In contrast, conservation of angular momentum rigorously forbids the emission of electrons at angles of $0°$ or $180°$ *without* spin-flip. Recently, measurements performed near $0°$ at the GSI Darmstadt [6] have confirmed the predicted angular distribution. In this way, the electron spin and magnetic transitions manifest themselves in a particularly clear-cut manner.

It is instructive to compare differential cross sections of the photoeffect with those of the corresponding radiative recombination [7]. For high velocities, the peak of the distribution for the photoeffect is increasingly shifted towards forward angles as an effect of the retardation. This means that the detailed structure is compressed into a narrow forward cone. On the other hand, owing to the Lorentz transformation to the laboratory system, the inverse process, RR, decompresses the peak so that details become more visible. Hence, REC (or RR) is the most practical way to study the photoelectric effect at high energies [8].

We have also performed an extensive tabulation of total cross sections for radiative recombination and, consequently, for the photoelectric effect of hydrogen-like ions with charge numbers $1 \le Z \le 112$ for the K, L, and M shells and electron energies ranging from closely above the threshold to the relativistic regime. The cross sections, accurate to three digits, are based on fully relativistic calculations including the effects of the finite nuclear size and all multipole orders of the photon field [9].

In view of the high precision obtainable for the differential cross section, it is meaningful to investigate QED corrections to the dynamics of photoionization and radiative recombination [10, 11].

References

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