Vacuum-Assisted Photoionization

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Introduction: Inner-shell photoionization of an atom or ion is one of the most basic processes between radiation and matter [1]. Ionization may proceed through the photoelectric effect or Compton scattering. However, when the photon energy $\hbar\omega$ exceeds twice the rest mass m of the electron, ionization may be catalyzed by the creation of an electron-positron pair from the Dirac vacuum. We call this process *vacuum-assisted photoionization* [2]. While at MeV photon energies and beyond, the cross sections associated with the photoelectric and Compton effect decrease with increasing photon energy essentially as $1/(\hbar\omega)$, the cross section associated with the vacuum-assisted photoionization increases, and then saturates. As a result, the most probable way of photoionizing an atom at high photon energies is to make the vacuum spark. We calculate the cross section for this new photoionization process which proceeds either via direct pair creation on an atomic electron with ionization of that electron or via pair creation on the atomic nucleus binding the electron followed by an electron-electron or an electron-positron encounter.

Pair creation with $e^{+/-}$-e^- encounter: In this case we may think of pair creation in the field of the atomic nucleus followed by knock-out of the bound electron by one of the outgoing particles of the produced e^+e^- pair. If E_B denotes the binding energy of an inner-shell, say K-shell, electron this process occurs with a threshold of $\hbar\omega_{threshold} = 2mc^2 + E_B$. Within a simple semiclassical model [2], the electron and the positron are created with equal probability anywhere inside a sphere of radius equal to the electron Compton wavelength $\lambda = \hbar/(mc)$ centered at the nucleus. Neglecting correlations between the points where the electron and the positron first appear and also any interaction between the two fermions, the probabilities $P_{+/-}$ for knocking out a bound electron are computed independently.

With these assumptions it is obvious that the cross section for the process in question is related to the Bethe-Heitler cross section σ_{PP} for nuclear field pair production by the relation

$$\sigma_1 = \sigma_{PP}\,(P_+ + P_-). \qquad (1)$$

For $\omega > \omega_{threshold}$ the total probability $P = P_+ + P_-$ for knocking out the bound electron is estimated [2] as

$$P = 2\,(\alpha^2 Z)^2\,\{1 - [1 - (\alpha^2 Z)^2]^{1/2}\}^{-1}, \qquad (2)$$

where α is the fine structure constant and Z denotes the nuclear charge number. For $\alpha Z \ll 1$, the probability is $4\alpha^2$ and it changes only slightly for heavier elements. With an essentially Z- and energy-independent probability, our estimate [2] for the cross section for pair production with K-shell ionization, when the latter appears through $e^- - e^-$ or $e^+ - e^-$ interaction, depends on atomic number and photon energy essentially as the Bethe-Heitler cross section for pair production. As a result, we expect roughly a Z^2 scaling as well as a saturation of the cross section at high photon energies due to screening effects.

Pair production in the field of a bound electron: In the case of pair production by a photon on an initially bound electron the presence of the nucleus is not required by kinematics. Due to change in mass of the particle producing the field in which the pair is created the threshold energy for production on a bound electron is different from that encountered for production on a heavy nucleus. In particular, for a pair to be produced in a collision of a photon with an electron at rest the photon energy must exceed $4mc^2$, i.e. twice the threshold energy for nuclear field pair production. Compared with the Bethe-Heitler cross section for pair production by photons, the calculation of the cross section for pair production in the field of an electron is considerable more complicated due to recoil and exchange effects. Here, retardation effects become important since the recoil velocity of the initial electron is not negligible in comparison with the speed of light c. Furthermore, one has to incorporate exchange effects associated with the indistinguishability of the two electrons and also radiative corrections. Only relatively recently an exact expression for the pair production cross section by a photon in the field of a *free* electron was obtained [3] by integrating the elements of the third order scattering matrix connecting one photon state and three fermion states. Eight Feynman diagrams have to be considered when exchange effects are incorporated (Fig. 1).

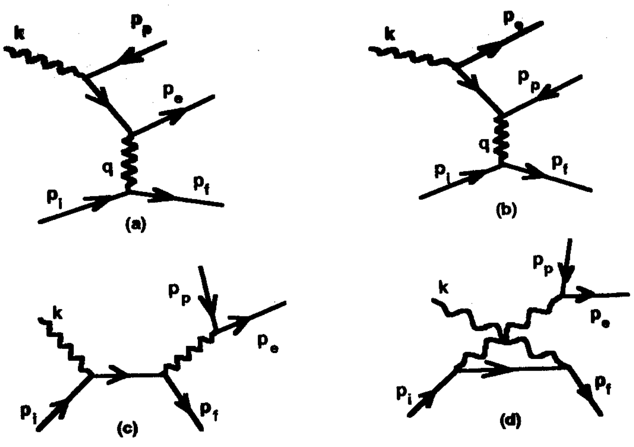

Fig. 1: *Feynman diagrams for pair production by a photon in the field of a free electron. The corresponding 4 exchange diagrams which are not shown in the figure are obtained by interchanging the final electron lines.*

For the process in which an incoming photon creates a pair in the field of a *bound* electron we use an analytic representation of the momentum transfer differential cross section $d\sigma_B/dq$ for pair production in the field of a *free* electron as derived by Borsellino [4]. Since in the case of a bound electron momentum can be transferred both in *excitation* and *ionization* one has to exclude the channels in which the atom ends up in an excited state. This may be achieved by requiring that the allowed minimum momentum transfer q_{min} equals the momentum transfer q_{cut} given by ($\hbar = m = c = 1$)

$$q_{cut} = [(1 + E_B)^2 - 1]^{1/2}, \quad (3)$$

that is needed to ionize the electron. The binding energy E_B of the initially bound electron is given by the Sommerfeld formula for hydrogen-like ions as $E_B = [1 - (\alpha^2 Z)^2]^{1/2}$ for the 1s-state. Neglecting screening effects that are of minor importance for photon energies in the MeV range and beyond, the total cross section $\sigma_2(k)$ for the vacuum-assisted photoionization process – regarded as pair creation in the field of a bound electron with the ionization of that electron – may be written [2] as

$$\sigma_2(k) = \int_{q_{cut}}^{q_M} dq(d\sigma_B / dq), \quad (4)$$

where k represents the photon momentum and q_M is the maximum allowed momentum transfer

$$q_M = \{ k(k-1) + (k+1)[k(k-4)]^{1/2} \} / (2k+1). \quad (5)$$

Results: In the following the cross section for the mechanism associated with pair production followed by electron-electron (positron) encounter will be refered to as σ_1, and the cross section for pair production by a photon in the field of a bound electron with ionization of that electron as σ_2.

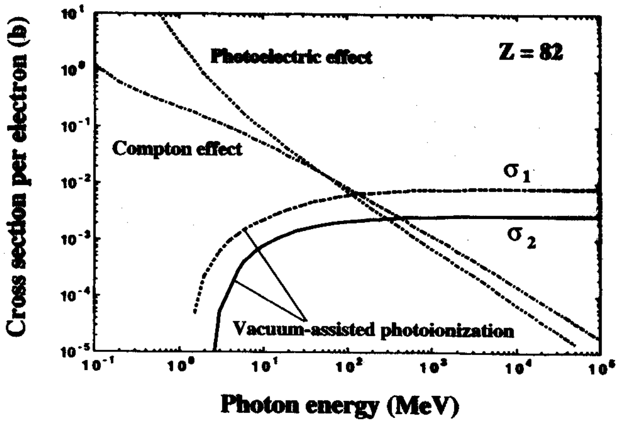

Fig. 2: *Cross sections for K-shell vacancy production in Pb.*

Figure 2 shows the cross sections for creation of a K-shell vacancy in lead ($Z = 82$) for different photoionization processes. The curves are drawn using tabulated values [5] for the photoelectric effect and Compton scattering, respectively. Note that the cross sections are given per electron and one has to multiply by a factor of two to account for both K-shell electrons. From Figure 2 one can see that the cross section for creation of a K–vacancy in Pb at photon impact energies below 1 MeV is dominated by the photoelectric effect. However, with increasing photon energy the photoelectric cross section decreases as a high negative power of the photon energy and then (above 10 MeV) as the inverse of the photon energy. The Compton cross section exhibits a slightly slower fall off. In contrast, the contribution from the vacuum-assisted photoionization process increases with increasing photon energy, starting from a threshold of approximately 1 MeV for σ_1 and 2 MeV for σ_2. The contributions from σ_1 and σ_2 saturate at 7.5 mb and 2.5 mb, respectively. The most important result displayed in Fig. 2 is that the total cross section for vacuum-assisted photoionization becomes comparable to the cross section for photoionization through Compton scattering and photoelectric effect for approximately 100 MeV photons and it dominates for higher energies. At 1 GeV, 90% of the cross section for creating a K-shell vacancy is due to contributions from vacuum-assisted photoionization. Pair production followed by electron-electron (positron) encounter provides the largest contribution to the cross section for the creation of a K-shell vacancy in Pb. This situation is reversed for Ca ($Z = 20$) as shown in Fig. 3.

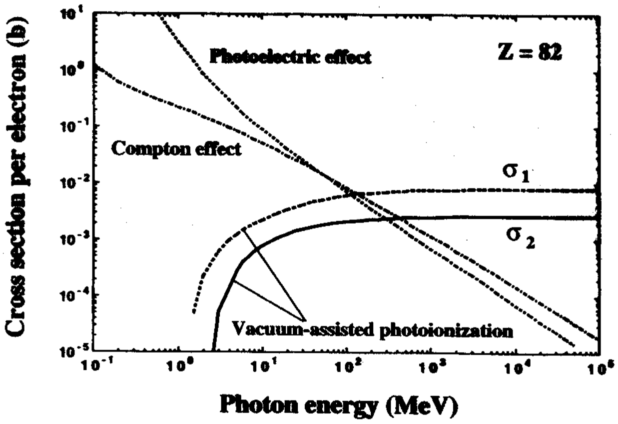

Fig. 3: *Cross sections for K-shell vacancy production in Ca.*

Here the largest contribution (σ_2) is associated with the pair production in the field of the bound electron. This process dominates for low-Z targets then decreases steadily as a consequence of the increased binding energy which requires higher and higher momentum transfer to free the bound electron. The contribution from pair production in the nuclear field followed by electron-electron or electron-positron encounter (σ_1) increases almost as the square of the nuclear charge number and subsequently dominates for high-Z atoms.

In conclusion, the most important prediction of the present investigation is that vacuum-assisted photoionization will dominate all other known photoionization processes in the highly relativistic energy domain. An interesting parallel can be made with the process of bound-free pair production [6] - also refered to as capture from the vacuum – which dominates other electron capture processes in relativistic ion-atom collisions. This behavior highlights the crucial role that the negative energy continuum plays in the relativistic regime in atomic collision processes.

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