Two-Photon Bremsstrahlung of Free Atoms

Rainer Hippler

Fakultät für Physik, Universität Bielefeld, Postfach 8640, D-4800 Bielefeld 1, Federal Republic of Germany

(Received 15 November 1990)

The two-photon bremsstrahlung emitted in collisions of 7–15-keV electrons with free (gaseous) argon, krypton, and xenon atoms was observed. The agreement with recent theoretical calculations is poor.

PACS numbers: 34.80.−i

The acceleration of electrons in the nuclear field of target atoms may give rise to the emission of a continuous spectrum of electromagnetic radiation. Since its first discovery by Röntgen in 1895,[1] this "bremsstrahlung" has been recognized as one of the most fundamental physical processes; besides, it has been proven to be of considerably practical relevance to various disciplines. In following decades, the production and the properties of bremsstrahlung radiation were explored quite thoroughly;[2–4] today, it is believed that the bremsstrahlung process is well understood and that the corresponding continuous spectrum can be calculated with fair accuracy. This is certainly true for the one-photon process; in contrast, little is known about two-photon or multiphoton bremsstrahlung processes. While other multiphoton processes are well known, for example, in atomic photoionization processes[5] and in free-free transitions,[6] the corresponding bremsstrahlung processes have attracted comparatively little interest over the years. A main reason for this may be found in the relatively small probability for emitting two or more bremsstrahlung photons in a single collision. To our knowledge, the only experimental attempt to investigate the two-photon bremsstrahlung process was performed by Altman and Quarles,[7] who investigated the two-photon process during 75-keV electron impact on solid gold. These authors observed an appreciable fraction of two-photon bremsstrahlung processes, more than 2 orders of magnitude larger than predicted by calculations based on different theoretical approaches.[8,9] The origin of this large discrepancy awaits further experimental and theoretical investigations. In this Letter we report experimental investigations of two-photon bremsstrahlung from free (gaseous) atoms. We have investigated the two-photon process for 7–15-keV electrons impinging on free argon, krypton, and xenon atoms. Because of the low target density used in the present work our results are obtained under conditions in which double scattering of the incident electrons is negligible.

The experimental arrangement essentially consists of an electron gun inside a vacuum chamber, a gas cell, two x-ray detectors, and the coincidence electronics. The vacuum chamber is made from stainless steel and is pumped by a turbomolecular pump with a pumping speed of 500 L/s; the residual gas pressure is a few times 10^{-7} mbar. The electron gun is of triode type and equipped with a directly heated tungsten filament. The extracted electron beam is focused by an electrostatic lens and, after passing two pairs of deflection plates, directed into the gas cell. During the measurements, the gas cell is maintained at a pressure of 10^{-3} mbar, which is low enough to ensure single-collision conditions. The electron beam inside the gas cell is viewed by two x-ray detectors which are mounted perpendicular to the electron beam and opposite to each other. One detector is a flow-mode proportional counter equipped with a 6-μm Hostaphan window; as the counter gas we use a 90%-Ar–10%-CH_4 mixture. This detector has a relatively low spectral resolution of about $\pm 25\%$ (full width at half maximum, FWHM) at 1.6-keV photon energy. The other detector is a lithium-drifted silicon [Si(Li)] detector equipped with a 50-μm Be window; the spectral resolution of this detector is 180 eV at 5.9 keV. Pulses from the two detectors are suitably amplified; for each detector two signals are derived. The "slow" signals are used to derive the required energy information; these signals are fed into single-channel analyzers (SCA) to select the energy windows of the detected photons. The SCA outputs enter into a coincidence unit (time resolution 4 μs) from which the gate signal for the multichannel analyzer (MCA) is derived. The "fast" signals are used for timing purposes; these are fed into constant-fraction discriminators to generate, after a suitably chosen delay, the "start" and "stop" signals for the time-to-amplitude converter (TAC). Output pulses from the TAC are stored on the MCA operated in the pulse-height mode which is gated by the coincident slow signals. The achieved time resolution is ≈ 200 ns.

From the measured coincidence signal N_c the fourfold differential cross section (with respect to the energies k_1 and k_2 and the emission angles Ω_1 and Ω_2 of the two photons) for the two-photon bremsstrahlung process was derived,

$$N_c = \frac{d^4\sigma}{dk_1\,dk_2\,d\Omega_1\,d\Omega_2}\Delta k_1 \Delta k_2 \Delta\Omega_1 \Delta\Omega_2 \epsilon_1 \epsilon_2 L n_a n_e \,, \quad (1)$$

where Δk_i and $\Delta\Omega_i$ are the photon energy window and solid angle of photon detector i, ϵ_i its efficiency, L the combined observation length of both detectors, n_a the atomic density, and n_e the number of incident electrons.

The coincidence signal was normalized to the number of singles counts $N_{\gamma i}$ in one detector,

$$N_{\gamma i}=\frac{d^2\sigma}{dk_i\,d\Omega_i}\Delta k_i\,\Delta\Omega_i\,\epsilon_i L_i n_a n_e\,, \tag{2}$$

where $d^2\sigma/dk\,d\Omega$ is the one-photon bremsstrahlung cross section. As mentioned before, the one-photon cross sections are well known and can be calculated with fair accuracy. Here we used the cross sections tabulated by Kissel, MacCallum, and Pratt;[10] the anisotropic emission of bremsstrahlung photons was taken into account.[11]

The measured fourfold differential cross section $d^4\sigma/dk_1dk_2d\Omega_1d\Omega_2$ for the two-photon process is displayed in Fig. 1 versus photon energy k_2; the photon energy $k_1=2.8$ keV and the incident energy $T=8.82$ keV. To facilitate comparison of different target gases, the cross section was divided by Z^2 (Z is the atomic number); this scaling is predicted by several theoretical calculations.[8,9] The two-photon cross section displays a pronounced decrease with increasing photon energy; its behavior is in marked disagreement with Born-type calculations[8,9] which differ by factors of up to 300 from the experiment. Similar discrepancies are also observed compared to more sophisticated calculations of Véniard, Maquet, and Gavrila[9] which predict a comparatively modest photon-energy dependence. In addition, at the lowest photon energy ($k_1=1.0$ keV) the experimental results display a significant departure from a Z^2 scaling, with the scaled two-photon cross section of xenon being about a factor of 5 larger compared to argon and krypton. A simple estimate further shows that at this particular point ($k_1=2.8$ keV, $k_2=1.0$ keV) the two-photon process when integrated over the energy resolution of the second photon detector ($\Delta k_2=\pm 0.25$ keV) and over the emission angle $\Delta\Omega_2$ (assuming isotropic photon emission) contributes $\approx 10^{-2}$ to the corresponding one-photon cross section; since other photon energies k_2 contribute as well, the relative yield of the two-photon process to the total bremsstrahlung cross section is even larger.

A similar behavior is observed at other energies. Figure 2 displays results for the two-photon process in xenon at $k_1=2.0$ keV and $T=10$ and 12.5 keV versus photon energy k_2. As before, the fourfold differential cross section shows a pronounced increase with decreasing photon energy k_2 which is significantly larger than predicted by Born-type calculations. For comparison, our results at $T=8.82$ keV and $k_1=2.8$ keV and the corresponding calculations of Véniard, Maquet, and Gavrila[9] are also

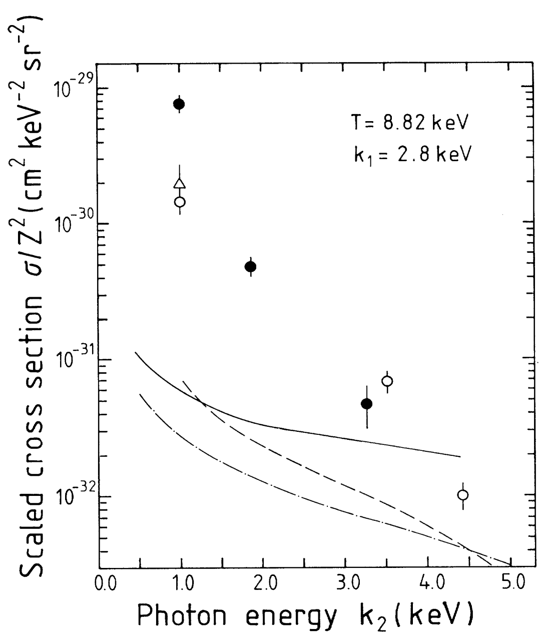

FIG. 1. Fourfold differential cross section divided by Z^2 for the two-photon bremsstrahlung process in argon (open triangles), krypton (open circles), and xenon (solid circles) vs photon energy k_2; the incident electron energy $T=8.82$ keV and the photon energy $k_1=2.8$ keV. Also shown is a theoretical calculation by Véniard, Maquet, and Gavrila (solid line, Ref. 9), a Born-type calculation (dash-dotted line, Refs. 8 and 9), and an estimate based on the alternative interpretation proposed by Lehtihet and Quarles (dashed line, Ref. 14; see text).

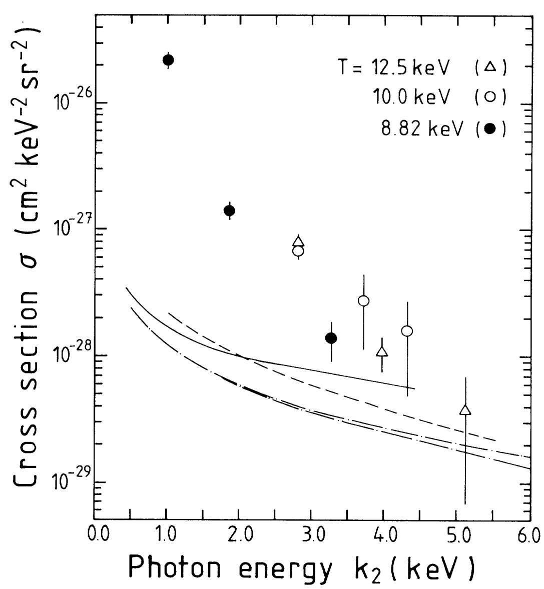

FIG. 2. Fourfold differential cross section for the two-photon bremsstrahlung process in xenon vs photon energy k_2 for incident energies $T=10$ keV (open circles) and 12.5 keV (open triangles); the photon energy $k_1=2.0$ keV. The dash-dotted lines (upper and lower curves are for $T=12.5$ and 10 keV, respectively) are the corresponding Born-type calculations (Refs. 8 and 9); the dashed line is an estimate based on the alternative interpretation proposed by Lehtihet and Quarles (Ref. 14; see text). For comparison, the present results (solid circles) and the theoretical calculations (solid line) by Véniard, Maquet, and Gavrila (Ref. 9) at $T=8.82$ keV and $k_1=2.8$ keV are also shown.

displayed. It should be noted that around $k = 4.1-5.4$ keV the bremsstrahlung spectrum overlaps with the characteristic Xe L transitions; the measured fourfold differential cross sections do not show any evidence for an enhancement of the two-photon process at these photon energies, however (Fig. 2).

In order to find some explanation for the observed discrepancies between experiment and theory at least two reasons come to mind. The first reason is the inadequacy of lowest-order perturbation theories. In our opinion, it appears questionable whether such calculations are indeed sufficient to provide a reasonable ground for the two-photon bremsstrahlung process. Second, one has to remember that the bremsstrahlung process is generally treated as an electron moving in the Coulombic field of a target atom. In a real atom other (bound) electrons exist which, in a static picture, account for a partial screening of the nuclear potential.[3] This neglects the dynamical aspect of the electron-electron interaction, for example, the polarization of the electron cloud by the incident electron. In principle, both types of interactions, namely, the "nuclear" electron-nucleus part and the "atomic" electron-electron part, contribute to the emission of photons.[12,13] In the one-photon process and for sufficiently large photon energies, these two parts are of comparable magnitude.[12] However, at relatively low photon energies close to the atomic transition energies the atomic part dominates. It appears likely that similar arguments also apply for the two-photon process.

Recently, an alternative interpretation of the large two-photon yield observed in the experiment of Altman and Quarles[7] was offered by Lehtihet and Quarles.[14] It is based on the assumption that the two-photon yield originates from a secondary process in which an incident electron is elastically scattered from the target to produce two photons in the Mylar window in front of either one of the two detectors. The major process for producing two x-ray photons in the window was identified as two-photon bremsstrahlung, whereas the two-photon emission by the same electron in two sequential single-bremsstrahlung events was found to be negligible. Based on estimates of what we believe are somewhat optimistic two-photon bremsstrahlung yields, these latter authors reached fair agreement with the previous experiment of Altman and Quarles.[7] In order to obtain reasonable agreement with the two-photon cross sections of Véniard, Maquet, and Gavrila[9] at the photon and electron energies of interest here, we first approximate the two-photon bremsstrahlung cross section by

$$\frac{d^4\sigma}{dk_1\,dk_2\,d\Omega_1\,d\Omega_2} \approx \frac{\alpha}{\pi}\frac{Z^2}{k_1k_2\beta^2}\frac{\sigma}{(4\pi\,\mathrm{sr})^2},$$

where $\alpha = 137.04^{-1}$ is the fine-structure constant, $\beta = v/c$ is the projectile velocity v divided by the speed of light c, and $\sigma \approx 5.6\times10^{-27}$ cm^2 is the scaled one-photon cross section tabulated in Ref. 10. Second, following the reasoning put forward by Lehtihet and Quarles,[14] we have calculated the (effective) cross section of the predicted alternative process as shown by the dashed lines in Figs. 1 and 2. As it turns out, the alternative process is insufficient to explain our experimental two-photon bremsstrahlung yield, particularly at low photon energies.

In conclusion, our results clearly show that (i) two-photon bremsstrahlung process exists and that (ii) its size as well as its photon-energy dependence is not in agreement with theoretical predictions. Work to investigate this discrepancy in more detail is in progress.

The help of Professor Dr. H. O. Lutz is gratefully acknowledged. Part of this work was supported by the Deutsche Forschungsgemeinschaft (DFG) in Sonderforschungsbereich No. 216 "Polarisation und Korrelation in Atomaren Stosskomplexen."

[1] W. C. Röntgen (translated by A. Stanton), Nature (London) **53**, 276 (1896).

[2] E.g., A. Sommerfeld, *Atombau und Spektrallinien, Band II* (Verlag Harri Deutsch, Thun, 1978).

[3] E.g., R. H. Pratt, in *Fundamental Processes in Energetic Atomic Collisions,* edited by H. O. Lutz, J. S. Briggs, and H. Kleinpoppen (Plenum, New York, 1983), p. 145; R. H. Pratt and I. J. Feng, in *Atomic Inner Shell Physics,* edited by B. Crasemann (Plenum, New York, 1983).

[4] E.g., R. Hippler, K. Saeed, I. McGregor, and H. Kleinpoppen, Phys. Rev. Lett. **46**, 1622 (1981).

[5] P. Agostini, F. Fabre, G. Mainfray, G. Petite, and N. K. Rahman, Phys. Rev. Lett. **42**, 1127 (1979); P. Kruit, J. Kimman, and M. J. van der Wiel, J. Phys. B **14**, L597 (1981); P. Kruit, J. Kimman, H. G. Muller, and M. J. van der Wiel, Phys. Rev. A **28**, 248 (1983); R. Hippler, H. J. Humpert, H. Schwier, S. Jetzke, and H. O. Lutz, J. Phys. B **16**, L173 (1983); R. Hippler, H. Schwier, H.-J. Humpert, and H. O. Lutz, Z. Phys. D **5**, 21 (1987); T. J. McIlrath, P. H. Bucksbaum, R. R. Freeman, and M. Bashkansky, Phys. Rev. A **35**, 4611 (1987); P. H. Bucksbaum, M. Bashkansky, R. R. Freeman, T. J. McIlrath, and L. F. DiMauro, Phys. Rev. Lett. **56**, 2590 (1986).

[6] A. Weingartshofer, J. K. Holmes, G. Caudle, E. M. Clarke, and H. Krüger, Phys. Rev. Lett. **39**, 269 (1977); A. Weingartshofer, E. M. Clarke, J. K. Holmes, and C. Jung, Phys. Rev. A **19**, 2371 (1979).

[7] J. C. Altman and C. A. Quarles, Phys. Rev. A **31**, 2744 (1985).

[8] V. Florescu and V. Djamoi, Phys. Lett. A **119**, 73 (1986).

[9] V. Véniard, A. Maquet, and M. Gavrila, Phys. Rev. A **35**, 448 (1987).

[10] L. Kissel, C. MacCallum, and R. H. Pratt, Sandia National Laboratories, Albuquerque, Report No. SAND81-1337, 1981 (unpublished).

[11] M. Aydinol, R. Hippler, I. McGregor, and H. Kleinpoppen, J. Phys. B **13**, 989 (1980).

[12] M. Ya. Amusia, in *The Physics of Electronic and Atomic Collisions,* edited by A. Dalgarno, R. S. Freund, P. M. Koch, M. S. Lubell, and T. B. Lucatorto, AIP Conf. Proc. No. 205 (American Institute of Physics, New York, 1990), p. 201.

[13] A. Dubois and A. Maquet, Phys. Rev. A **40**, 4288 (1989).

[14] H. E. Lehtihet and C. A. Quarles, Phys. Rev. A **39**, 4274 (1989).