Journal of Atomic, Molecular, Condensate & Nano Physics
Vol. 4, Nos. 1 – 3, pp. 15–20, 2017
ISSN 2349-2716 (online); 2349-6088 (print)
Published by RGN Publications

http://www.rgnpublications.com

Bremsstrahlung of Fast Electrons near Fano Resonance with Account for Polarization Channel

Research Article

F.B. Rosmej[1,2,3,4,*], V.A. Astapenko[4] and V.S. Lisitsa[3,4,5]

[1] *Sorbonne University, Faculty of Science and Engineering, UMR 7605, case 128, 4 Place Jussieu, F-75252 Paris Cedex 05, France*
[2] *LULI, Ecole Polytechnique, CNRS-CEA, Physique Atomique dans les Plasmas Denses - PAPD, Route de Saclay, F-91128 Palaiseau Cedex, France*
[3] *National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Institute of Laser and Plasma Technologies, Plasma Physics Department, Kashirskoe sh. 31, Moscow 115409, Russia*
[4] *Moscow Institute of Physics and Technology - MIPT, Institutskii per. 9, Dolgoprudnyi 141700, Russia*
[5] *National Research Center "Kurchatov Institute", Kurchatov sqr. 1, 123182 Moscow, Russia*
Corresponding author: frank.rosmej@sorbonne-universite.fr

Abstract. We investigate the Bremsstrahlung originating from fast non-relativistic electron scattering on an atom in the spectral region near the Fano resonance including the polarization channel and interference term. It is shown that the account for polarization Bremsstrahlung leads to a significant increase of the total Bremstrahlung cross section near the Fano resonances. Numerical calculations are carried out for the first autoionization states $2l2l'$ of the Helium atom in the framework of the Born approximation that goes beyond the dipole approximation of the dynamic polarizability of the atom.

Keywords. Bremsstrahlung; Polarization Bremsstrahlung; Helium atom; Fano resonance

PACS. 32.90.+a

Received: December 27, 2017 **Accepted:** December 30, 2017

1. Introduction

When an electron is scattered on an atom, Bremsstrahlung (BrS) can be emitted via two channels. The first one is the well-known ordinary Bremsstrahlung (OB) and the second channel is polarization Bremsstrahlung (PB) [1]. OB originatesfrom the acceleration of the charge in the atomic electric field while PB can be described as a scattering of the projectile own field on the electronic core of the atom. Another interpretation of PB (appropriate especially for non-relativistic projectiles) is the radiation of alternating dipole moment of an atom induced by the incident charged particle.

BrS that includes the polarization channel was investigated for different targets and projectiles over the past several decades. Although, the results have been summarized in monographs [2,3] several interesting cases have not been considered. One of them is the BrS of electron scattering by atomic autoionizingstates. These states have high resonance polarizability and consequently the PB cross section may be large that facilitates experimental detection.

The present paper is therefore devoted to the investigation of BrS in the spectral range near theFano resonances while numerical examples are worked out that are of mutual interest for theory and experiment.

2. Methods of Calculation

We consider BrS of fast but non-relativistic electron scattering on the helium atom in the spectral range near the first autoionization state $\omega \approx \omega_0 = 60.1$ eV, where ω_0 is the resonance frequency. The spectral BrS cross section can be presented as a sum of three terms corresponding to ordinary BrS, polarizarion BrS and interference term [2,3]:

$$\frac{d\sigma_{tot}}{d\omega} = \frac{d\sigma_{OB}}{d\omega} + \frac{d\sigma_{PB}}{d\omega} + \frac{d\sigma_{int}}{d\omega}. \tag{1}$$

In the first Born approximation for non-relativistic incident electron these cross sections have the form (we use atomic units throughout the paper):

$$\frac{d\sigma_{OB}}{d\omega} = \frac{16Z^2}{3c^3v^2\omega}\int_{\omega/v}^{2v}(1-\widetilde{F}(Q))^2\frac{dQ}{Q}, \tag{2}$$

$$\frac{d\sigma_{PB}}{d\omega} = \frac{16\omega^3}{3c^3v^2}|\alpha(\omega)|^2\int_{\omega/v}^{2v}\widetilde{F}(Q)^2\frac{dQ}{Q}, \tag{3}$$

$$\frac{d\sigma_{int}}{d\omega} = \frac{32Z\omega}{3c^3v^2}\mathrm{Re}[\alpha(\omega)]\int_{\omega/v}^{2v}(1-\widetilde{F}(Q))\widetilde{F}(Q)\frac{dQ}{Q}. \tag{4}$$

Here v is incident electron velocity, c is speed of light, Z is nuclear charge, Q is momentum transferred from the incident electron to an atom, $\alpha(\omega)$ is dipole dynamic polarizabilty of an atom, $\widetilde{F}(Q)$ is normalized atomic form-factor equal to:

$$\widetilde{F}(Q) = F(Q)/Z \tag{5}$$

with

$$F(Q) = \frac{4\pi}{Q}\int_0^{\infty} \rho(r)\sin(Q)r\,dr, \tag{6}$$

ρ is radial distribution of electron density in atom. Equations (3) and (4) have been obtained employing the non-dipole approximation of the scattering tensor [4] according

$$\alpha(\omega,Q) \approx \widetilde{F}(Q)\,\alpha(\omega). \tag{7}$$

The imaginary part of dynamic polarizabiltyis calculated from the optical theorem:

$$Im\{\alpha(\omega)\} = \frac{c}{4\pi\omega}\sigma_{abs}(\omega). \tag{8}$$

For real part of polarizability the Kramers-Kronig relation is valid:

$$Re\{\alpha(\omega)\} = \frac{c}{2\pi^2}\int_0^{+\infty} \frac{\sigma_{abs}(\omega') - \sigma_{abs}(\omega)}{\omega'^2 - \omega^2}d\omega', \tag{9}$$

where $\sigma_{abs}(\omega)$ is absorption cross section of the atom.

In the vicinity of Fano resonance the absorption cross section has the form [5]:

$$\sigma_{abs}(\omega) = \sigma_0 \frac{\left(q + \frac{2(\omega-\omega_0)}{\Gamma}\right)^2}{1 + \left(\frac{2(\omega-\omega_0)}{\Gamma}\right)^2}. \tag{10}$$

ω_0 is the resonance frequency, Γ is the spectral width of the resonance, q is Fano parameter, σ_0 is photo-absorption cross section without contribution of the autoionization state. We suppose that $\sigma_0 \cong$ const in following consideration.

Substituting (10) in (9) one can find an explicit expression for the real part of the polarizability in the near-resonance spectral range [6]:

$$Re\{\alpha(\omega)\} = \frac{c\sigma_0}{4\pi^2\Gamma\left[\frac{(\omega-\omega_0)^2}{\Gamma^2} + \frac{1}{4}\right]}\left[\frac{1-q^2}{4} - \frac{\omega - 2\omega_0}{\left(4\frac{\omega_0^2}{\Gamma^2}+1\right)\Gamma}\left(\frac{\omega_0}{\Gamma}(q^2-1)+q\right)\right]. \tag{11}$$

Equations (1)-(12) permit analyzing the role of PB in the total BrS.

3. Numerical Results and Discussions

The results of cross section calculations for total BrS, OB and PB are presented in Figure 1 for the velocity of the incident electron equal to 30 at.u.scattering on Helium atom. For the first Fano resonance in He we have $\omega_0 = 60.1$ eV, $\Gamma = 0.038$ eV, $q = -2.8$, $\sigma_0 \cong 0.055$ at.u. [7].

The resonance character of the PB can be clearly seen from Figure 1 while the OB cross section is practically constant in the considered frequency range.

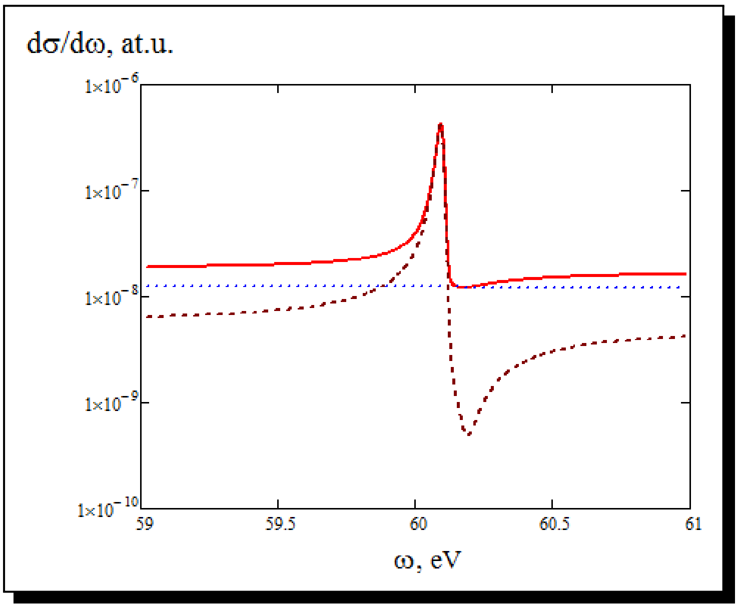

Figure 1. Cross sections of total BrS (solid line), OB (dotted line) and PB (dashed line) in the vicinity of the first autoionization state of He atom.

The role of the PB is characterized by Figure 2 in which the cross sections ratios between different BrS channels are presented. One can see from Figure 2 that PB dominates in the frequency range near the Fanoresonance which is determined by the spectral width Γ. The maximum ratio between total and ordinary BrS cross section is equal to a factor of 35. Out of the resonance the OB cross section exceeds the PB cross section by the factor of 3-5.

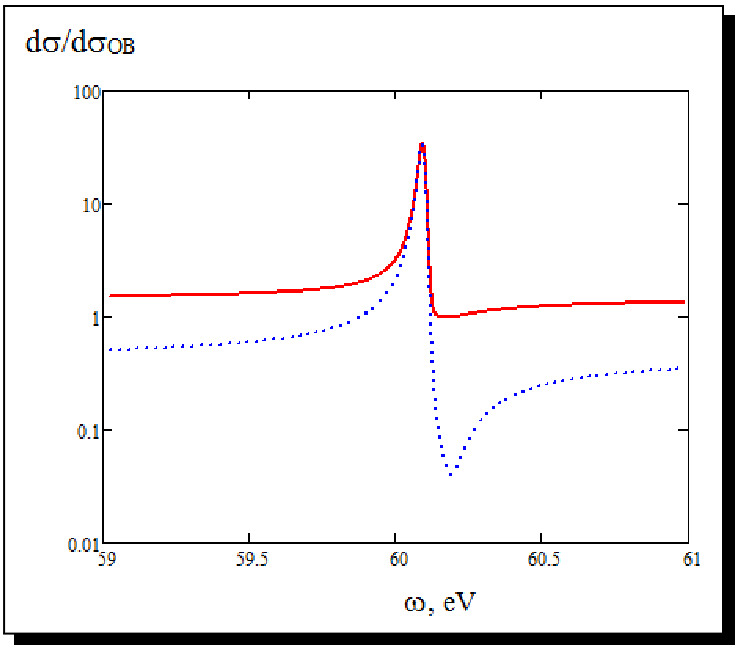

Figure 2. Ratio between total BrS and OB (solid line) and between PB and OB (dotted line) in the vicinity of the first autoionization state of He atom.

To analyze the contribution of the interference term let us introduce a summary BrS cross section according

$$\frac{d\sigma_{sum}}{d\omega} = \frac{d\sigma_{OB}}{d\omega} + \frac{d\sigma_{PB}}{d\omega}. \qquad (12)$$

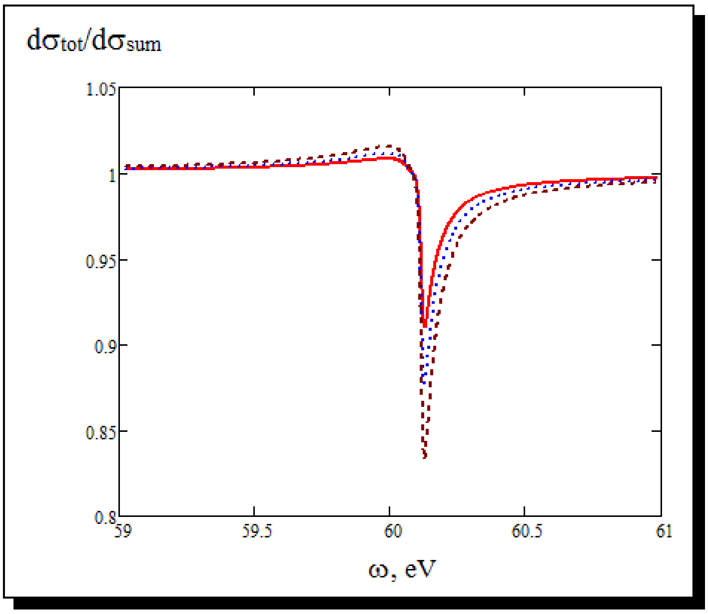

Figure 3. Ratio between total and summary cross section for different velocities of the incident electron: solid line: $v = 50$ a.u., dotted line: $v = 20$ a.u., dashed line: $v = 10$ a.u.

The ratio between total cross section (1) and summary cross section (12) is shown in Figure 3 for different velocities (in atomic units) of the incident electron. One can see that the contribution of the interference term does not exceed 18% at small velocities. This contribution decreases with the increase of the electron velocity and has a negative sign in frequency range: $\omega > \omega_0$.

4. Conclusion

We have investigated the Bremsstrahlung of fast non-relativistic electron scattering on Helium atoms in the spectral range near the first Fano resonance taking into account the polarization channel of the Bremsstrahlung that goes beyond the dipole approximation as well as the interference term. It is shown that polarization Bremsstrahlung dominates over ordinary Bremsstrahlung in the narrow spectral range in the vicinity of resonance frequency while the width of this critical spectral range is of the order of the Fano resonance width. Numerical calculations demonstrate that the ratio between the polarization Bremsstrahlung and the ordinary Bremsstrahlung cross sections may reach 1-2 orders of magnitude near the maximum of the spectral distribution while the interference term does not exceed some 10% while it has negative sign at the high-frequency wing of the resonance. The large enhancement factors near the resonance might be advantageous for experimental observation.

Acknowledgements

This research was supported by the Cooperation Agreement between the "University Pierre and Marie Curie, Sorbonne Universities" AND the "Moscow Institute of Physics and Technology – MIPT", by the Moscow Engineering Institute (MEPhI), by the Government order of the Ministry of Education and Science of the Russian Federation (project No. 3.9890.2017/8.9) and by EcolePolytechnique (LULI, Palaiseau).

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

The authors wrote, read and approved the final manuscript.

References

[1] V.N. Tsytovich and I.M. Oiringel (eds.), *Polarization Bremsstrahlung*, Springer (1992).

[2] V. Astapenko, *Polarization Bremsstrahlung on Atoms, Plasmas, Nanoscructures and Solids*, Springer (2013).

[3] A.V. Korol and A.V. Solov'yov, *Polarization Bremsstrahlung*, Springer (2014).

[4] F.B. Rosmej, V.A. Astapenko and V.S. Lisitsa, XUV and x-ray elastic scattering of attosecond electromagnetic pulses on atoms, *J. Phys. B* **50**, 235601 (2017).

[5] U. Fano, Effects of configuration interaction on intensities and phase shifts, *Phys. Rev.* **124**, 1866 (1961).

[6] V.A. Astapenko and E.S. Khramov, Scattering of ultrashort electromagnetic pulses on fano resonance, *International Review of Atomic and Molecular Physics* **7** (2), 53 (2016).

[7] J.A.R. Samson and W.C. Stolte, Precision measurements of the total photoionization cross-sections of He, Ne, Ar, Kr, and Xe, *Journal of Electron Spectroscopy and Related Phenomena* **123**, 265 (2002).