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

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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 Bremsstrahlung 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

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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 originates from 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 autoionizing states. 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 the Fano 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 $\omega \approx \omega_0 = 60.1 \text{ eV}$, where $\omega_0$ 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]:

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

(1)

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

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

(2)

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

(3)

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

(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 polarizability of an atom, $\tilde{F}(Q)$ is normalized atomic form-factor equal to:

$$
\tilde{F}(Q) = F(Q)/Z
$$

(5)
with
\[ F(Q) = \frac{4\pi}{Q} \int_0^\infty \rho(r) \sin(Qr) \, dr, \]
(6)
\( \rho \) 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
\[ \alpha(\omega, Q) \approx \tilde{F}(Q) \alpha(\omega). \]
(7)
The imaginary part of dynamic polarizability is calculated from the optical theorem:
\[ \text{Im} \{\alpha(\omega)\} = \frac{c}{4\pi\omega} \sigma_{\text{abs}}(\omega). \]
(8)
For real part of polarizability the Kramers-Kronig relation is valid:
\[ \text{Re} \{\alpha(\omega)\} = \frac{c}{2\pi^2} \int_0^{+\infty} \frac{\sigma_{\text{abs}}(\omega') - \sigma_{\text{abs}}(\omega)}{\omega'^2 - \omega^2} \, d\omega', \]
(9)
where \( \sigma_{\text{abs}}(\omega) \) is absorption cross section of the atom.

In the vicinity of Fano resonance the absorption cross section has the form (5):
\[ \sigma_{\text{abs}}(\omega) = \sigma_0 \left( \frac{q + \frac{2(\omega - \omega_0)}{\Gamma}}{1 + \left(\frac{2(\omega - \omega_0)}{\Gamma}\right)^2} \right)^2. \]
(10)
\( \omega_0 \) is the resonance frequency, \( \Gamma \) is the spectral width of the resonance, \( q \) is Fano parameter, \( \sigma_0 \) is photo-absorption cross section without contribution of the autoionization state. We suppose that \( \sigma_0 \equiv \text{const} \) 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):
\[ \text{Re} \{\alpha(\omega)\} = \frac{c\sigma_0}{4\pi^2\Gamma \left[\frac{(\omega - \omega_0)^2}{\Gamma^2} + \frac{1}{4}\right]} \left[ 1 - q^2 - \frac{\omega - 2\omega_0}{4\omega_0^2} \left( \frac{\omega_0}{\Gamma} (q^2 - 1) + q \right) \right]. \]
(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 \( \omega_0 = 60.1 \text{ eV}, \Gamma = 0.038 \text{ eV}, q = -2.8, \sigma_0 \simeq 0.055 \text{ at.u.} \) [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 Fano resonance which is determined by the spectral width $\Gamma$. 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

\[
\frac{d\sigma_{\text{sum}}}{d\omega} = \frac{d\sigma_{OB}}{d\omega} + \frac{d\sigma_{PB}}{d\omega}.
\]

(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.
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Competing Interests

The authors declare that they have no competing interests.

Authors’ Contributions

The authors wrote, read and approved the final manuscript.

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