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Thick-target X-ray bremsstrahlung spectra produced in 6.5 keV and 7.5 keV e^--Hf collisions

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Abstract. The absolute doubly differential cross-sections (DDCS) for production of the thick-target X-ray bremsstrahlung spectra in collisions of 6.5 keV and 7.5 keV electrons with thick Hf target are measured. The X-ray photons are counted by a Si(Li) detector placed at 90° to the electron beam direction. The bremsstrahlung spectra are corrected for various 'solid-state effects' namely, electron energy-loss, electron back-scattering, and photon-attenuation in the target, in addition to the correction for detector's efficiency. The DDCS values after correction, are compared with the predictions of a most accurate thin-target bremsstrahlung theory [H K Tseng and R H Pratt, *Phys. Rev.* **A3**, 100 (1971); Kissel *et al*, *Atomic Data Nucl. Data Tables* **28**, 381 (1983)]. Also, a dependence of the absolute DDCS on atomic number Z of the targets ($_{47}$Ag, $_{79}$Au and $_{72}$Hf) at 7.0 keV and 7.5 keV electron energies has been studied. The agreement between experiment and theory is found to be satisfactory within 27% systematic error of measurements. However, an apparent systematic difference between experiment and theory in the region of low-energy photons has been explained qualitatively by considering the fact that the hexagonal atomic structure of Hf offers possibly a greater magnitude of 'solid-state effects' in respect of blocking the low-energy bremsstrahlung photons from coming out of the target surface than does the cubic-face centered structure of Ag and Au target in similar conditions of the experiment.

Keywords. Bremsstrahlung photons; absolute doubly differential cross-sections; solid-state effects; photon-attenuation; electron back-scattering.

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1. Introduction

When energetic electrons pass through the matter, they are accelerated in Coulomb fields of atomic nuclei and their surrounding electrons emitting a non-characteristic radiation called 'bremsstrahlung (BS)'. The intensity, energy spectrum and angular distribution of BS depend on incident energy and angle of incidence of the electrons as well as on the material and shape of the target [1]. The data on 'absolute' intensity (cross-section), energy and angular distribution of electron-induced BS photons produced in thick-targets are important for studies in nuclear radiation transport, shielding, dosimetry and in other applications. Although considerable amount of information is available on the BS process, accurate predictions on thick-target BS production are especially difficult to make in the low-energy region where the initial kinetic energy of electrons is a few keV. This difficulty arises in part from the uncertainties in the BS cross-sections in this energy region and in part from the complicated calculations required to account for 'target-effect', for example, multiple scattering, photon-attenuation, and back-scattering of the incident electrons in the considered material. An early useful review of the experimental and the theoretical informations on BS is given by Koch and Motz [2]. An exhaustive survey of the experiments is given by Nakel [3]. A comparison between theoretical single-collision cross-sections and experimental data is presented by Tseng and Pratt [4]. These comparisons show that simpler analytical approximations agree with experimental data in some particular ranges of electron and photon energies. The exact screening (ES) numerical calculations [4] agree satisfactorily with experimental data for all energies of the electron and that of the photon. A good agreement has been found between experimental data [5, 6] and ES calculations, although some discrepancies have been reported in high Z-targets for incident energy of 10 keV [5].

Recent experimental work on BS photon energy spectra and on their angular distributions has used the solid-state detectors to measure directly the number of photons produced at a given angle as a function of the photon energy [5–7]. Thus, the experiments directly measure the doubly differential cross-section (DDCS) or $\mathrm{d}^2\sigma/\mathrm{d}k\mathrm{d}\Omega$, which is a function of the incident electron energy T, the atomic number of the target atom Z, the photon emission angle θ_k, with respect to the incident electron beam direction, and of the radiated photon energy k. The DDCS tables for incident electron energies ranging from 1 keV to 500 keV and for Z from 1 to 92 have been published by Kissel *et al* [8]. By considering the ratio of DDCS for two different targets at the same T and the same θ_k, we have obtained the relative shape of the BS photon energy spectrum in 7.0 keV e^--Ag, Au collisions to a precision of better than 4% [9]. The thick-target BS absolute intensity distributions as a function of k for 7.0 keV electrons incident on Ag and Au targets have been compared with predictions of the semi-classical formulations [10, 11], wherein the agreement between experiment and calculations was found to be fairly satisfactory [12]. In one of our recent papers, the absolute doubly differential cross-sections for BS spectra produced in 7.0 keV e^--Ag, Au collisions have been measured [13]. The agreement between experiment and theory for DDCS of BS photons emitted at $\theta_k = 90°$ with respect to the incident electron beam direction was found to be satisfactory both in magnitude as well as in shape within the experimental uncertainty of measurements.

The present work on the measurement of absolute DDCS of BS photons produced in collisions of 6.5 keV and 7.5 keV electrons with a thick Hf target forms, firstly, the extension and support to our data published recently [13] and secondly, throws light on a probable difference, if there is any, between the strength of 'solid-state effects' on production of BS X-ray photons by Hf and that by Ag and Au targets at similar impact energies. This difference is expected to arise due to the nature of transport of incident electrons and exiting photons inside the volume of a 'cubic-face centered' atomic structure of Ag and Au targets in contrast to that in the 'hexagonal' structure of Hf target [14]. The absolute DDCS for BS photon emission have been determined after treating the experimental data with necessary corrections. These corrections essentially take account for different types of 'solid-state effects' which are expected to be present in a thick-target, for example, multiple scattering, photon-attenuation, electron back-scattering and electron energy-loss due to inelastic events. The comparison of the results after correction yields a reasonable agreement with the predictions of a thin-target theory [4, 8] both for shape as well as for absolute magnitude within the experimental systematic error of about 27%.

2. Theoretical formulations

The absolute DDCS can be determined by experiment using a relation,

$$\mathrm{d}^2\sigma/\mathrm{d}k\mathrm{d}\Omega = N_{\mathrm{B}}(k)/[N_0 t\epsilon(k)\Delta k\Delta\Omega], \tag{1}$$

where, $N_B(k)$ is the number of BS photon counts at a photon energy k, t is the target thickness, $\epsilon(k)$ is the detector's efficiency at a photon energy k, Δk is the width of the photon energy window, $\Delta\Omega$ is the solid angle subtended by the photon detector on the target.

The theoretical DDCS are tabulated in [8] in terms of the scaled photon energy spectrum $(\beta_1^2/Z^2)k(\mathrm{d}\sigma/\mathrm{d}k)$ and the shape function S, defined as,

$$S(Z,\theta_k,k/T,T) = (\mathrm{d}^2\sigma/\mathrm{d}k\mathrm{d}\Omega)/(\mathrm{d}\sigma/\mathrm{d}k), \tag{2}$$

where, β_1 is incident electron speed in units of the speed of light. The experimental data for DDCS are plotted as a function of photon energy radiated per incident electron energy k/T, and are finally compared with the theoretical DDCS obtained by using (2) and the tabulated values of DDCS from [8]. In these comparisons, the experimental parameters such as $N_{\mathrm{B}}(k)$ and N_0 involved in (1) were obtained after treating them with due solid-state corrections. The details of these corrections are given in [13] and briefly in §4. Also, the dependence of DDCS on atomic number of the target (Z) is examined for data of 7.0 keV electrons incident on Ag and Au foils and for 7.5 keV electrons on Hf target at the chosen values of k/T. The nature of variation of DDCS versus Z at different k/T values is presented and discussed in §5.

3. Experimental method

Details of the experimental arrangement have been described elsewhere [9, 15]. Briefly, a collimated beam of 7.5 keV electrons having a spot size of about 3.0 mm was incident on a thick Hf target (6.6 mg/cm^2) and the collisionally induced bremsstrahlung X-ray photons were detected at an angle of 90° to the incident electron beam direction by a Si(Li) detector (FWHM = 250 eV at 5.9 keV). The beam current of about 1.0 nA was monitored on the insulated target itself and the recorded spectra were corrected for background. Methods for the energy calibration of the spectra, the background subtraction, and for the determination of the detector's efficiency were followed on the same lines as described in [12, 13, 16]. The background photons produced by scattered electrons from walls of the chamber or those from its window foil (a hostaphan-foil of thickness 6μ) were prevented from reaching the detector by using a suitable circular aperture of $\phi = 3.0$ mm in front of the Be-window. A typical contribution of the background was found to be less than 1% per channel.

4. Data analysis

A typical BS X-ray photon energy spectrum for 6.5 keV electrons on Hf target at 90° is shown in figure 1. The spectrum shows a continuous BS intensity distribution as a function of photon energy with a broad peak around $k = 4.0$ keV and with a high energy 'tip' at a maximum energy of the incident electrons. The cut-off feature of low energy photons below about $k = 2.25$ keV arises due to poor efficiency of the detector and that to a partial absorption of X-rays in the target employed. The observed intensity of BS photons at energy k, $N_{\rm B}(k)$ has been corrected for detector's efficiency, electron back-scattering and for photon-attenuation in the target. Evaluation of these corrections has been given in detail in [13] and they are only briefly described in the following sub-sections.

4.1 Electron energy-loss

The incident electron loses its energy in exciting and ionizing the target atoms while it scatters-off inelastically by them. As a result, it slows down as it progresses through the target and eventually its energy reaches the Fermi level of the target material and finally it flows from specimen to earth. The stopping power or rate of loss of energy per unit mass-path length traversed by the electron in the target is given by Bethe and Ashkin [17],

$$-\mathrm{d}E/\mathrm{d}(\rho x) = 78500(Z/AE)\ln(1.166E/J), \tag{3}$$

where, E is the incident electron energy (keV), Z is the atomic number of the target atom, ρ is the density of the target (gm/cm^3), x is the thickness of the target (cm) and $J = 13.5Z$ (eV), the mean ionization energy of the target atom [18]. The Hf target of high purity (99.99%) was obtained commercially whose thickness was quoted accurate to within 20% by the manufacturer. In the present case, $x = 5.0 \times 10^{-4}$ cm. The total electron energy losses for 6.5 keV and for 7.5 keV electrons in the target were calculated using (3) with the assumption that all electrons traverse the same target thickness. The energy-loss for

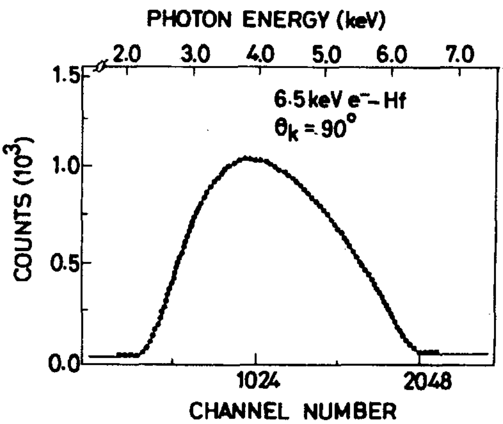

Figure 1. A typical bremsstrahlung X-ray photon energy spectrum produced in 6.5 keV e^--Hf collisions. Photons are detected at $\theta_k = 90°$ with respect to the incident electron beam direction.

6.5 keV and for 7.5 keV electrons traversing the above thickness was found to be 100% for each case. The ranges of penetration for 6.5 keV and 7.5 keV electrons in Hf target are found to be 5.26×10^{-5} cm and 6.08×10^{-5} cm respectively. These ranges were used to calculate the photon-attenuation in the target for X-rays of different energies.

4.2 Electron back-scattering

An average electron back-scattering correction $R_{E,k}$ which depends on the energy of the radiated photon is given by [19],

$$R_{E,k} = (1-\eta)/(1-\eta x^2); \quad x \equiv k/E, \tag{4}$$

where, η is the fraction of incident electrons which are elastically scattered in backward direction, it is termed as 'back-scattering coefficient'.

The relevant η values were taken from [20]. The electron back-scattering losses affecting N_0 (1) were found to vary from 14% to 40% for 6.5 keV electrons, and from 14% to 43% for 7.5 keV electrons on Hf in a photon energy range of $k = 2.0$–7.5 keV. The corresponding corrections were made in the analysis accordingly.

4.3 Photon-attenuation

The bremsstrahlung photons generated during the penetration of the impinging electrons on the target suffer a considerable absorption by the target material depending on the take-off angle α of the emerging photons and on the mass absorption coefficient μ_k/ρ and on the target thickness x. The correction for photon-attenuation in the target material for the present geometry was made by using the following expression [11],

$$f_{E,k,\alpha} = \exp(-\mu_k x/\tan\alpha) \tag{5}$$

where, μ_k is the total attenuation coefficient at a photon energy k, whose value was obtained from [21]. The photons are attenuated by a target thickness $x/\tan\alpha$ ($\alpha = 45°$ in the present geometry). The photon-attenuation was found to vary from 13% to 90% for 6.5 keV electrons and from 12% to 91% for 7.5 keV electrons in Hf target for photons of energy $k = 7.5$ keV and 2.0 keV respectively. The determination of the absolute efficiency of the Si(Li) detector in the photon energy range of $k = 2.0$ keV to 7.0 keV was made on the lines as described in [16]. After including the various corrections for experimental parameters contained in (1), we have determined the absolute DDCS for the BS spectra and have compared them with the thin-target theoretical calculations given by Kissel *et al* [8].

5. Results and discussion

The absolute DDCS of BS photons emitted from 6.5 keV and 7.5 keV electrons colliding with HF thick target are plotted as a function of photon energy radiated per incident electron energy (k/T) and are shown in figures 2 and 3 respectively. The data have been

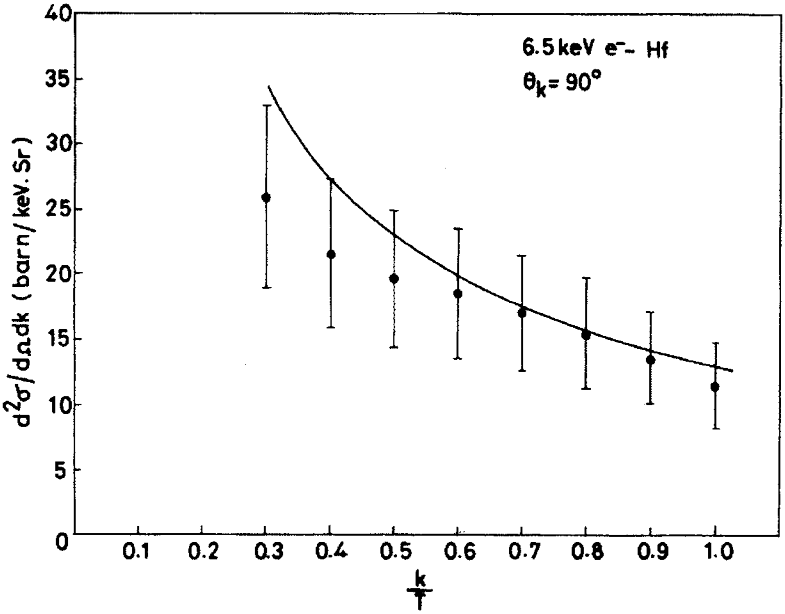

Figure 2. Absolute doubly differential cross-sections, $\mathrm{d}^2\sigma/\mathrm{d}k\mathrm{d}\Omega$ (barn/keV.sr) for bremsstrahlung photons emitted from 6.5 keV electrons colliding with a Hf target (filled circles), as a function of the photon energy radiated per incident electron energy, k/T. The solid line curve is theory [8]. Error bars represent the systematic error of measurements.

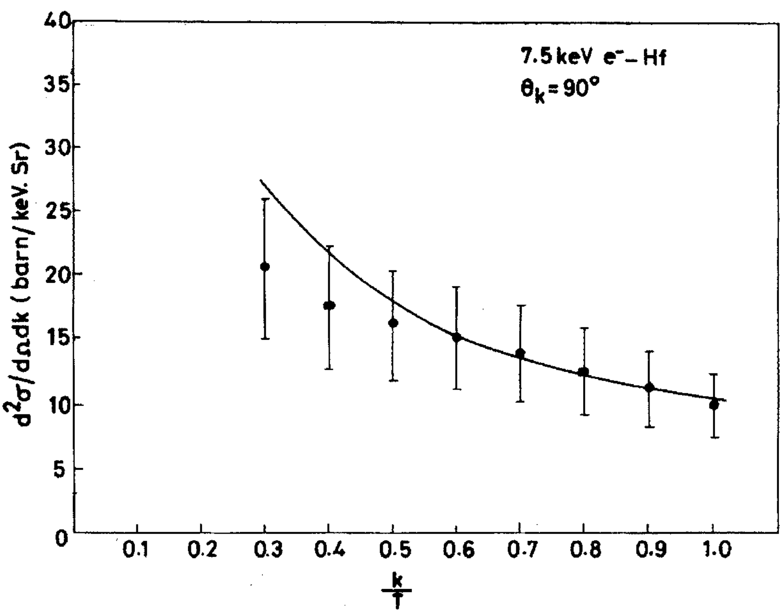

Figure 3. Same as in figure 2 except for 7.5 keV electrons incident on Hf target (filled circles).

compared with the theoretical calculations of Kissel *et al* [8] who have treated the BS process as a single electron transition in the relativistic, self-consistent, screened central potential of the target atom. The calculations are carried out in a partial-wave expansion and are exact for first order in quantum electrodynamics.

At both incident energies, the experimental data with error bars are seen to follow the theoretical predictions. The overall agreement between experiment and theory is seen to be satisfactory within the systematic error of measurement of about 27%. This error arises due to uncertainties in target thickness ($\sim$ 20%), detector's absolute efficiency ($\sim$ 17%), counting statistics ($\sim$ 3%) and in beam energy ($\sim$ 1%). The large uncertainty in detector's efficiency comes mainly from the determination of the solid angle of the detector $(1.73 \pm 0.29) \times 10^{-4}$ sr. It may be mentioned here that the target thickness uncertainty is a constant error and not a point-to-point error in these plots. The efficiency error is a point-to-point error and it should be the same for each angle of photon detection. It should, however, be pointed out that the overall discrepancy between experiment and theory may partly arise due to the following reasons:

(a) The theory used for comparison is based on a 'thin-target' formulations.

(b) The back-scattering correction has been assumed to be photon angle independent.

(c) The electron's straggling and its diffusion process in the target are difficult to assess and have been neglected.

(d) The high energy photons ("tip" photons) are generated mainly from single collisions with atoms on the surface or near the surface, it is not surprising that the surface of the target may get contaminated in presence of an oil-diffusion pump backed by an oil-filled rotary pump. As a consequence, a substantial fraction of the residual gases are hydrocarbons, which can polymerise at or close to the surface of the target by bombardment of the electron beam and cause an undesirable build-up of contamination. This contamination causes a decrease in intensity of the BS photon because a part of the energy of electrons is dissipated in the contamination for its excitation/ionization. Further, the deposited material will absorb the generated X-ray photons causing their reduction and lowering the DDCS values.

(e) The random motion of penetrating electrons into the target and the depth-distribution of the generated photons inside the target are not considered in the present analysis. Both of these effects are complicated in nature and they are qualitatively expected to reduce the intensity of the BS photons.

There are; however, few apparent systematic differences between experiment and theory (see figures 2 and 3), particularly in the region of low-energy photons, which need some clarifications. Specifically, the data for both impact energies under consideration are systematically lower than the theory at each value of $k/T < 0.5$, however, there is a fairly good agreement between experiment and theory for data over $k/T > 0.5$. We can offer no conclusive experimental explanation for this trend, although the following possibility can be suggested to account for this observation:

Referring back to the question whether a hexagonal structure of Hf plays a relatively different role in production of BS photons or behaves closely to that of Ag and Au targets. When one compares the trend of variation of absolute DDCS as a function of k/T for

Ag, Au and for Hf with respective theoretical predictions at about similar impact energies, it is observed that experimental data are consistently underestimated by the theory by a difference of as large as 34% at the lowest value of the measured k/T for Hf target, while there is an excellent match between experiment and theory for the similar lowest k/T data for Ag and Au targets [13]. This observation may be taken to interpret qualitatively that the low energy photons have much lower probability to come out from the Hf target surface compared to those from the Ag and Au in similar experimental conditions. This effect may be further corroborated by the fact that the atomic structure of the Hf target is a 'hexagonal close packed (hcp)' while that of the Ag and Au is a 'face-centered cubic (fcc)'. In general, the hcp-structure is more tightly packed compared to the fcc-structure [14]. Thus, the low-energy BS photons are expected to suffer frequent collisions with the Hf atoms and lose their energy relatively faster during their emergence from inside volume than that with the Ag and the Au targets. Hence, at present it is our conjecture that the 'hexagonal' atomic structure of Hf offers possibly a larger magnitude of solid-state effects for the low-energy photons in respect of blocking them from coming out of the target than does the 'cubic-face centered' structure of Ag and Au targets in the similar experimental conditions.

Figure 4 shows the dependence of absolute DDCS of BS photon emission as a function of atomic number Z of the target in collisions of 7.0 keV electrons with Ag and Au (data taken from [13]) and 7.5 keV electrons with Hf target (present data) at three typical k/T values, namely at $k/T = 0.3$, 0.6 and 1.0. Error bars are of the same dimensions as those in figures 2 and 3. The data have been compared with theoretical predictions of Kissel *et al* [8]. There is an overall good agreement between experiment and theory for all k/T

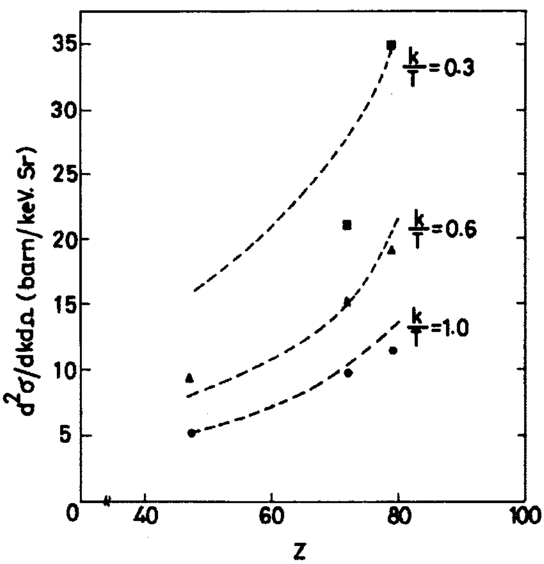

Figure 4. Variation of the absolute doubly differential cross-sections, $d^2\sigma/dkd\Omega$ (barn/keV.sr) as a function of atomic number Z of the targets; Ag, Hf and Au for $k/T = 0.3$ (■), 0.6 (▲) and 1.0 (•) in 7.0 keV e^--Ag, Au and 7.5 keV e^--Hf collisions. Dotted curves represent the theoretical predictions [8]. Error bars (not shown) are similar to ones shown in figures 2 and 3.

values under consideration except for one scattered datum for Hf at $k/T = 0.3$. The above comparison shows that the thin-target theory of Tseng and Pratt [4] and of Kissel *et al* [8] gives a satisfactory agreement with the experiment provided the data are properly corrected for various solid-state effects as described in §4.

6. Conclusions

The absolute DDCS for thick-target X-ray BS photons produced in 6.5 keV and 7.5 keV electrons colliding with a thick Hf target are measured using a Si(Li) detector at 90° to the incident beam direction. The photon energy data have been corrected for different solid-state effects, for example, electron energy-loss, back-scattering, photon-attenuation in the target and for detector's efficiency. The corrected intensities of photon energy spectra are used to determine the absolute DDCS of BS photons and are compared with a most accurate theory available today which is based on thin-target formulations. Also, a dependence of the absolute DDCS on atomic numbers of three targets, namely $_{47}$Ag, $_{72}$Hf, and $_{79}$Au at 7.0 keV and 7.5 keV electron energies for typical values of $k/T = 0.3, 0.6$, and 1.0 has been studied. The agreement between experiment and theory is satisfactory and it is found to be well within 27% systematic error of measurements. Comparison of DDCS data for Ag, Au and Hf at the similar impact energies, however, shows that there exists an apparent systematic discrepancy between experiment and theory for Hf target, particularly in the region of low-energy photons. It may be qualitatively explained by considering the fact that the 'hexagonal' atomic structure of Hf offers possibly a greater magnitude of hindrance to low-energy photons in coming out from the considered depth of the target than does the 'cubic-face centered' structure of Ag and Au.

The other solid-state effects which may be present but not considered here, are suggested to arise partially from the random motion of the penetrating electrons in the target and that from the depth-distribution of the photons generated inside the target. As a matter of fact, the two effects tend to reduce the BS photon intensity. A rigorous theory which considers these effects in thick-targets is needed to be developed so that a direct comparison with experimental data may provide a deeper insight into the knowledge of thick-target effects in production of BS photons by the keV-electrons.

For comparing the thin-target theoretical calculations with experiment for absolute DDCS of BS photon production at electron impact energies in the keV range, the experimental data are essentially desired from the gaseous targets in a single collision condition. The work in this direction is already in progress in our laboratory.

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