Alternative interpretation of the double atomic-field bremsstrahlung experiment

H. E. Lehtihet and C. A. Quarles
Texas Christian University, Fort Worth, Texas 76129
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A recent experiment reported a two-order-of-magnitude enhancement of the cross section for double atomic-field bremsstrahlung when compared to various theoretical formulations. In this paper we propose to explain the observed coincidence rate in terms of the coherent emission of two thick-target bremsstrahlung photons from the Mylar vacuum window by electrons elastically scattered in the target. The photon energy dependence of the coincidence rate predicted by this thick-target double bremsstrahlung (TTDB) model is estimated and compared to the previous experimental results for a gold target. Fairly good agreement is obtained with both the order of magnitude of the coincidence rate and its photon energy dependence, even though a crude approximation is used to estimate the TTDB distribution from the better known thick-target single bremsstrahlung spectrum.

I. INTRODUCTION

In 1985, Altman and Quarles[1] reported a coincident two-photon rate when thin-film targets were bombarded by 75-keV electrons. The observed rate was interpreted as double bremsstrahlung (DB) from the atomic field and was found to be more than two orders of magnitude larger than that predicted by the relativistic Born approximation theory of Smirnov.[2] This rather large discrepancy, combined with the complexity of the theoretical cross section and disagreement among earlier theoretical formulations,[3,4] suggested that more theoretical work was needed.

On the other hand, the measured coincidence rate was statistically different from zero at the two to three standard-deviation level and was probably at the limit of the available coincidence detection possibilities. The principal experimental difficulty is the small size of the DB cross section, which makes the measurement particularly susceptible to the possibility of significant background from other two-photon processes in the experimental setup used.

An exact relativistic calculation is to date still unavailable. However, two theoretical efforts have recently been made in an attempt to resolve this problem. Florescu and Djamo[5], and independently, Veniard *et al.*,[6] have carried out nonrelativistic calculations in the dipole approximation. Although nonrelativistic, these calculations do not have the same limitations as the Born approximation and thus are useful for testing the experiment where high-Z targets and low energies were used. The cross section obtained was systematically higher than that of Ref. 2 by a factor of 2 to 3 as expected, but was still much smaller than that found experimentally.

These new theoretical results strongly suggested a reinterpretation of the observed rate. Several additional plausible two-photon processes that were not considered in Ref. 1 and that could have competed with DB were then evaluated.[7] The analysis clearly showed that the interpretation in Ref. 1 of the experimental rate as solely due to DB in the target overestimates the cross section. However, under the most stringent assumptions, the contribution of these competing processes did not seem to be able to account for the discrepancy observed.

One question that was raised concerned the nature and contribution of two-photon processes originating in thick targets such as the walls of the scattering chamber, the target holder, and the detector windows. These processes were not well understood and, to our knowledge, there has been no published work on coincident two-photon processes induced by electrons in thick targets. Here we propose a model, based on thick-target double bremsstrahlung (TTDB) in the detector windows, that offers order-of-magnitude agreement with the observed coincidence rate and that seems to resolve the discrepancy. This model was suggested by preliminary results[8] obtained in a different experiment aimed at understanding electron-induced thick-target two-photon effects by direct measurement of the two-photon coincidence rate from the bombardment of thick targets with electrons from a radioactive source.

A review of the experimental and theoretical results for the DB cross section and a summary of the analysis of competing processes is given in Sec. II. The TTDB model is described and compared to the experiment in Sec. III, and conclusions are given in Sec. IV.

II. REVIEW OF THE PRESENT SITUATION

The experimental layout of Ref. 1 is shown in Fig. 1. A beam of 75-keV electrons from a Cockcroft-Walton accelerator was incident on a thin-film target held in the middle of a scattering chamber by an aluminum holder. The targets used consisted of thin foils (30–60 $\mu g/cm^2$) deposited on a 15-$\mu g/cm^2$ carbon backing, and the target material ranged from $Z=47$ to 92. The photons produced were detected in coincidence by two solid-state detectors placed outside the scattering chamber at 90° and 270° to the incident-beam direction. The scattering chamber was kept under vacuum and photons were transmitted to each detector crystal through first a 1-mil Mylar vacuum window, then a small air space and finally a 0.3-mil Be window.

The coincidence technique used to process the detector output signals and extract the rate R_{expt} of photons in coincidence is described in detail in Ref. 1. Neglecting

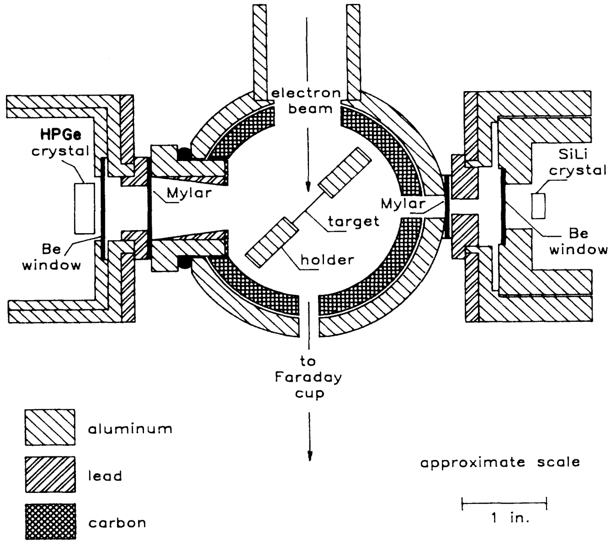

FIG. 1. Experimental layout used in Ref. 1. The width of both Mylar and Be windows is exaggerated. HP Ge represents high-purity Ge.

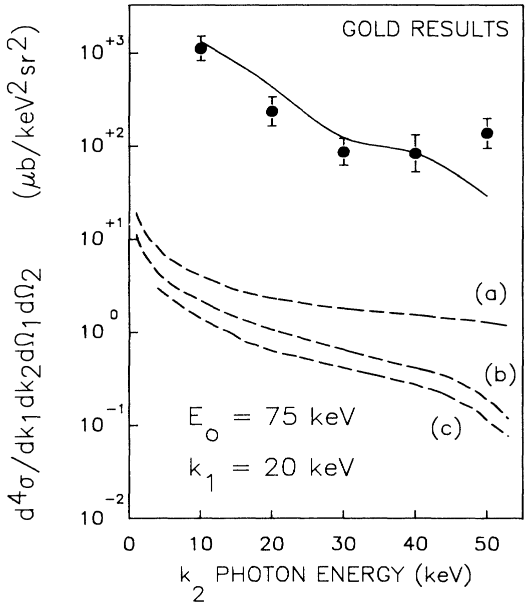

FIG. 2. Differential DB cross section obtained for a gold target as a function of one-photon energy while the other photon energy is held fixed. The results obtained in Ref. 1 for $Z=79$, $E_0=75$ keV, and $k_1=20$ keV vs k_2 are shown with the associated error bars. The result of the present TTDB model was evaluated using Eq. (6) at the experimental data points and is shown as the solid line. The dashed lines represent various thin-target models: (a) nonrelativistic dipole approximation (Ref. 6); (b) nonrelativistic Born approximation (Ref. 6); (c) relativistic Born approximation (Refs. 1 and 2).

the small photon attenuation in Mylar and Be windows, this experimental rate can be expressed in terms of R_0 the incident electron rate and t the target thickness,

$$R_{\mathrm{expt}}=R_0 t(\Delta k_1 \Delta\Omega_1 \varepsilon_1)(\Delta k_2 \Delta\Omega_2 \varepsilon_2) d\sigma_{\mathrm{expt}} . \quad (1)$$

For each detector, $\Delta\Omega$ is the subtended solid angle and ε is the efficiency averaged over Δk the corresponding energy window of detection. The product $\varepsilon\Delta\Omega$ was determined, for each detector, in a separate experiment that used the same geometry to measure the known single bremsstrahlung (SB) spectrum. The proportionality factor $d\sigma_{\mathrm{expt}}$ was measured for various energies of one photon while the second photon energy was held fixed. The results obtained are reproduced in Fig. 2 for a gold target. If, as in Ref. 1, this experimental factor is interpreted as $d\sigma_{\mathrm{DB}}$, the cross section for DB in the target differential in photon energies and solid angles, then a significant discrepancy is found. The thin-target DB predictions are shown as the dashed lines: (a) nonrelativistic dipole approximation;[6] (b) nonrelativistic Born approximation;[6] and (c) relativistic Born approximation.[1,2] If, on the other hand, the theory provides the correct order of magnitude for DB, as stressed by the work of Refs. 5 and 6, then the contribution of other two-photon processes must be included. Thus $d\sigma_{\mathrm{expt}}$ should be interpreted as a sum over all contributing effects including DB: $d\sigma_{\mathrm{expt}}=d\sigma_{\mathrm{DB}}+\sum_i d\sigma_i$.

The small size ($\sim 3\ \mu\mathrm{b\,sr^{-2}\,keV^{-2}}$ for gold) of the theoretical $d\sigma_{\mathrm{DB}}$ makes the enumeration of comparable two-photon processes both a necessary and a difficult task. Let R be the theoretical DB coincidence rate expected for a gold target. Up to now, a number of competing processes that can produce two photons in coincidence have been found which contribute a rate to the experiment of the same order as R. The experimental rate to be explained, on the other hand, is about $100R$.

A sizable background could be produced by interactions which originate in the target holder, which could be seen by both detectors in the arrangement of Fig. 1. Electrons scattered in the collimator upstream of the target, or backscattered in the Faraday cup or chamber wall after passing through the target, could hit the target holder and produce two photons by either DB or two SB processes. Estimates of the contributions depend upon the amount of thick-target single bremsstrahlung (TTSB) observed in the singles photon spectrum. While under some adverse conditions these effects could be large, under the conditions of Ref. 1, the contribution from these effects in the target holder is estimated to be less than $2R$. Photons produced in the upstream collimators could hit the target holder and produce two photons by double Compton scattering. This effect is estimated to contribute less than $0.1R$.

The important experimental observation that the coincidence rate scales with the target Z^2 tends to rule out the above processes and suggests that any competing process must originate in the target, considerably reducing the number of other possibilities. Several competing processes were considered in Ref. 1 and estimated to make small contributions to the coincidence rate. The estimated rate from additional background effects that begin in the target with a Z^2-dependent cross section includes the following: (1) $\sim R$ from elastic scattering (ES) by an incident electron into the target holder followed by DB in the holder; (2) $\sim 0.1R$ from SB in the target followed by either a second SB or double Compton event in the holder or windows. Processes that begin with ionization in the target contribute less than $0.1R$.

Adding all competing effects yields a total rate that could be as much as five times larger than that expected from the theoretical $d\sigma_{DB}$, but that is still much smaller than the rate measured. These considerations, while they demonstrate that the rate observed in Ref. 1 was not due solely to DB, do not explain the observed rate.

III. THICK-TARGET MODEL

The model we propose here begins with the Z^2-dependent ES in the target, then the scattered electron is stopped in one of the Mylar windows. The stopping electron loses energy principally by ionization. The radiative electron energy loss appears mainly as TTSB radiation. However, the emission of two photons in coincidence can also occur and can be detected because, as shown in Fig. 1, each Mylar window is seen by both photon detectors. Figure 3 shows two experimentally indistinguishable cases that can occur in both Mylar windows. The first case, which was referred to before as TTDB, describes the coherent emission of two photons by the same electron. The second case is the incoherent emission of a photon by two different but correlated electrons.

The contribution of the coherent TTDB effect to the observed coincident two-photon rate is

$$R_{\mathrm{TTDB}} = R_0 t \Delta k_1 \Delta k_2 \varepsilon_1 \varepsilon_2 (\Delta\Omega_1' \Delta\Omega_{11} \Delta\Omega_{12} + \Delta\Omega_2' \Delta\Omega_{22} \Delta\Omega_{21}) \times \mathcal{D}(k_1, k_2) d\sigma_{\mathrm{ES}}/d\Omega' , \quad (2)$$

where $d\sigma_{\mathrm{ES}}/d\Omega'$ is the ES scattering cross section at 90°, $\Delta\Omega_i'$ is the solid angle subtended by Mylar window i from the target, and $\Delta\Omega_{ij}$ is the solid angle subtended by detector j from Mylar window i. $\mathcal{D}(k_1,k_2)$ represents the TTDB distribution of photons produced per electron incident on the Mylar window and is in units of $(\mathrm{sr\,keV})^{-2}$. There is no available theory for $\mathcal{D}$, but a plausible order-of-magnitude expression can be derived from $\mathcal{S}$, the better-known TTSB distribution.

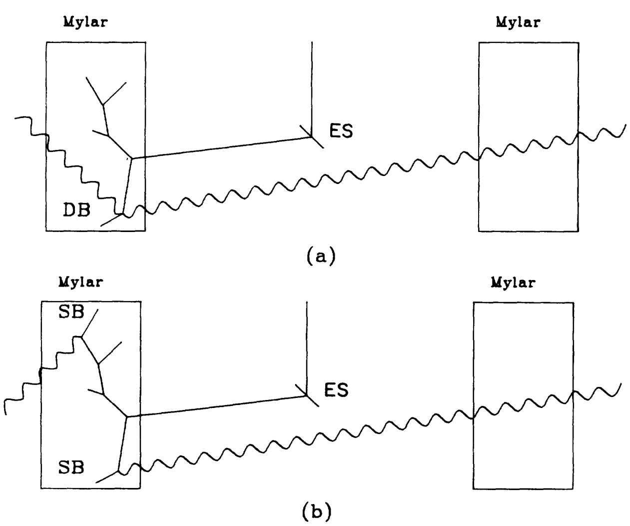

FIG. 3. Schematic of the thick-target bremsstrahlung model of elastic scattering (ES) in the target into a Mylar window followed by multiple ionization collisions with two-photon emission either as (a) coherent emission of two photons by the same electron; or (b) incoherent emission of one photon by two different but correlated electrons.

The contribution of the incoherent effect is evaluated in a similar fashion by replacing, in (2), $\mathcal{D}(k_1,k_2)$ by the product $\mathcal{S}(k_1)\mathcal{S}(k_2)$.

A. Thick-target single bremsstrahlung (TTSB)

Storm[9] has calculated the TTSB distribution by direct integration of the thin-target SB distribution over the target thickness assuming a continuous slowing-down approximation for the electron energy loss with target depth. When electron backscattering out of the target and photon attenuation is neglected, this integral can be written as

$$\mathcal{S}(k) = \int_{E>k}^{E_0} dE \left[\frac{d\sigma_{\mathrm{SB}}}{d\Omega\, dk} \right] \frac{1}{-dE/dt} , \quad (3)$$

where E_0 is the incident electron energy, E the electron energy at photon emission, and dE/dt is the electron energy loss per unit thickness. Using tabulated dE/dt available for tungsten and the Sommerfeld-Born approximation, Storm evaluated $\mathcal{S}(k)$ and obtained good agreement with both experiment and with an earlier empirical formula for the TTSB distribution given by[9]

$$\mathcal{S}(k) = \frac{27.6}{4\pi} \times 10^{-7} Z(E_0 - k)/k \ (\mathrm{sr\,keV})^{-1} , \quad (4)$$

where Z is the atomic number, which for the case of interest here would be that of the Mylar window, $Z \approx 6$.

Except for the constant term, the general form of (4) can be easily understood. The Z dependence arises from the fact that SB scales as Z^2 and dE/dt scales as Z. The ratio of the SB cross section to dE/dt is essentially independent of E, since both behave as E^{-1}. Hence the integral is proportional to $(E_0 - k)$. The k^{-1} dependence follows from the well-known k dependence of SB.

B. Thick-target double bremsstrahlung (TTDB)

The TTDB distribution can be obtained in analogy with the TTSB distribution. Using the thin-target DB cross section in place of the SB cross section, we can write

$$\mathcal{D}(k_1,k_2) = \int_{E>k_1+k_2}^{E_0} dE \left[\frac{d\sigma_{\mathrm{DB}}}{d\Omega_1 d\Omega_2 dk_1 dk_2} \right] \frac{1}{-dE/dt} . \quad (5)$$

Although a numerical evaluation of (5) is conceivable using tabulated values of dE/dt and numerical integrals of the fully differential DB thin-target cross section to obtain the term in large parentheses in (5), we have not attempted that here. Rather, we have used simple arguments, similar to those of Sec. III A, to obtain what we believe is a good order-of-magnitude expression for the TTDB effect. This approach should be accurate enough to determine whether the TTDB model is a plausible explanation of the discrepancy found in Ref. 1.

Based on the results of Smirnov[2] we find, first, that like the SB cross section, the DB cross section scales with Z^2. Second, the photon-energy dependence of DB is essentially $1/k_1 k_2$. Third, like SB, DB scales with E^{-1}, so the ratio of DB to dE/dt is also essentially independent of E. These assumptions about the behavior of DB are based on the simple expression obtained by Smirnov at the limit of nonrelativistic energies and are confirmed by our own numerical evaluation of the general case. Furthermore, in the limit where the second photon is soft, the DB cross section reduces to the product of the SB (Bethe-Heitler) cross section and the probability of emission of a second photon. This probability is proportional to α, the fine-structure constant. Hence, the behavior of the DB cross section with incident energy, radiated photon energy, and atomic number is essentially the same as that of SB.

Thus we propose that the TTDB distribution be approximated by a formula analogous to the TTSB distribution of (4), where the constant term has been multiplied by an additional factor of α to take into account the radiation of the second photon

$$\mathcal{D}(k_1,k_2) \approx \alpha\frac{27.6}{4\pi}\times 10^{-7} Z(E_0-k_1-k_2)/(k_1k_2)\ (\mathrm{sr\,keV})^{-2}\ , \tag{6}$$

where all energies are expressed in keV.

C. Prediction of the model

Because of the thick-target nature of this model, it becomes meaningless to evaluate a cross section and one should instead estimate the predicted coincidence rate. Here however, for purpose of comparison with the previous thin-target interpretation of the experimental results, we can express the rate R_{TTDB} given by (2) in terms of an effective differential cross section $d\sigma_{\mathrm{TTDB}}$ to be compared to $d\sigma_{\mathrm{expt}}$. Following (1) we rewrite (2) as

$$R_{\mathrm{TTDB}} = R_0 t(\Delta k_1 \Delta\Omega_1 \varepsilon_1)(\Delta k_2 \Delta\Omega_2 \varepsilon_2) d\sigma_{\mathrm{TTDB}}\ , \tag{7}$$

with

$$d\sigma_{\mathrm{TTDB}} = \left[\frac{\Delta\Omega_1'\Delta\Omega_{11}\Delta\Omega_{12}+\Delta\Omega_2'\Delta\Omega_{22}\Delta\Omega_{21}}{\Delta\Omega_1\cdot\Delta\Omega_2}\right] \times \mathcal{D}\, d\sigma_{\mathrm{ES}}/d\Omega'\ . \tag{8}$$

This effective cross section was evaluated for conditions that were as close as possible to that of the experiment. As described in Sec. II, the solid angles in the denominator of (8) were experimentally deduced for each detector from the separate measurement of the known SB spectrum. It was then possible to obtain the effective diameter of each detector to geometrically estimate the solid angles in the numerator. The results obtained for $d\sigma_{\mathrm{TTDB}}$ are shown as the solid line in Fig. 2 and are in good agreement with the order of magnitude of the experimental data points. The agreement with the photon-energy dependence is reasonable except for the point at 50 keV where the TTDB model underestimates the experiment. Perhaps there was a small contamination of this point from Compton backscattering from one detector to the other;[1] or perhaps the model simply does not treat the region near the endpoint adequately.

Replacing $\mathcal{D}$ in (8) by the product of two TTSB distributions yields the prediction for the incoherent effect. Because the constant term in (4) is much smaller than $\frac{1}{137}$, the contribution of the incoherent process is negligible in comparison with the coherent process. This process was already considered in Ref. 1, and estimated to be a small effect.

IV. SUMMARY

We have proposed a model based on coherent two-photon radiation in a thick target that explains the order of magnitude of the coincidence rate observed in Ref. 1. Using reasonable assumptions, the TTDB distribution was approximated from the known TTSB expression. The results obtained with this simple model demonstrate that the TTDB effect can be a significant background in any DB experiment, and therefore must be taken into account when designing a new experiment.

The previous experimental setup was particularly susceptible to a large TTDB background mainly because each Mylar window was seen by both detectors. Clearly, the experimental layout can be improved by placing the detectors in a more forward position relative to the incident beam direction and shielding them from direct line of sight of each other. Another way to eliminate or reduce the TTDB background is to perform a triple coincidence experiment that detects the scattered electron in addition to the two photons.

Aside from its role as a background in DB experiments, the TTDB process is very interesting in its own right and deserves detailed study. For example, a more accurate expression for the TTDB distribution can be obtained by a direct evaluation of (5) using tabulated electron energy-loss data and the DB cross sections from Refs. 2, 5, or 6. Also the TTDB process can be directly measured. Work is now in progress using thick-foil targets of silver, tantalum, gold, and lead bombarded by electrons emitted by a Cd-109 radioactive source.[8]

ACKNOWLEDGEMENTS

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