Absolute Doubly Differential Cross Sections for Electron Bremsstrahlung from Rare Gas Atoms at 28 and 50 keV

Sal Portillo* and C. A. Quarles

Department of Physics and Astronomy, Texas Christian University, Fort Worth, Texas 76129, USA
(Received 4 June 2003; published 23 October 2003)

Absolute doubly differential bremsstrahlung cross sections from Xe, Kr, Ar, and Ne have been measured for electron bombarding energies of 28 and 50 keV. Bremsstrahlung photons have been detected at 90° to the incident electron beam at energies ranging from 5 keV up to the kinematic end point. The results are compared with predictions of ordinary bremsstrahlung and of total bremsstrahlung that include polarizational bremsstrahlung from the target atom calculated in the stripping approximation. All previous absolute cross sections have been from thin-film solid targets and have not shown any polarizational bremsstrahlung contribution. The present results, the first from free atoms, provide definitive evidence for the contribution of polarizational bremsstrahlung to the photon spectrum from electron bremsstrahlung.

DOI: 10.1103/PhysRevLett.91.173201 PACS numbers: 34.80.–i, 78.70.–g

Introduction.—Until the 1970s bremsstrahlung was considered to be due solely to the acceleration of the electron in the field of the atom. Theoretically it was treated as a single electron transition in the continuum in a screened Coulomb potential. There have been both nonrelativistic and relativistic treatments. The relativistic calculation of Tseng and Pratt [1] formed the basis of a widely used tabulation of bremsstrahlung cross sections [2]. There have been several reviews of ordinary bremsstrahlung (OB) [3–6].

In the early 1970s, several people began to consider the target atom in a more realistic way: as a structured object that could be polarized by the incoming electron [7–10]. In this view, there is an addition to OB that arises from the dynamic polarization of the target electrons from the field of the passing charge. This additional contribution has been called "atomic" or "polarizational" bremsstrahlung (PB). Whereas the atomic number is sufficient to characterize the target atom for OB, the dynamic atomic polarizability is needed to determine the PB amplitude. Unlike the OB amplitude, the PB amplitude has structure associated with the characteristic frequencies of the target atom. Thus the total amplitude for bremsstrahlung from a structured target consists of the amplitude for OB from the accelerated projectile and the PB amplitude from the dynamically polarized target electrons. There have been a number of reviews of PB [11–13].

There have been many electron bremsstrahlung experiments on the photon energy spectrum and angular distribution (see reviews in Refs. [3,6,14–20]). Up to the present it has been possible to describe all of the data well by OB alone without assuming any contribution from the PB amplitude.

This failure to see evidence of the PB amplitude in the photon spectrum has been puzzling since PB has been observed in two cases where it significantly dominates OB. The first case is in the region of giant atomic resonances [21–26]. The effect is seen as an enhancement of photon emission in the neighborhood of the $n = 3$, 4, or 5 shells in appearance potential spectroscopy. The effect has been attributed to PB [13,27,28]. An increase in radiation in a narrow photon energy band off resonance has also been observed at electron energies below 2 keV and attributed to additional bremsstrahlung accompanying inelastic electron scattering [29,30]. The second case is proton bremsstrahlung, where OB is suppressed by the large mass of the projectile. In proton collisions, Ishii, Morita, and co-workers have accounted for bremsstrahlung from secondary electrons and from the target electrons in the field of the projectile and have measured an additional radiation that they attribute to PB [31–37].

However, all recent absolute cross section experiments have been on thin-film solid targets [14,19]. With self-supporting thin-film solid targets the error in the absolute cross section measurements has been rather large due to the uncertainty in target thickness [19]. Furthermore, there is the question of whether the PB amplitude could be suppressed in a solid target [38]. There is the well-known Landau-Pomeranchuk-Migdal effect at much higher energy [39], but so far no calculations have been done at lower energy. Finally, there have been only a few experiments on free atom targets [15–18] and none, until the present work, have been absolute cross section measurements.

In the present experiment, the absolute doubly differential cross section for electron bremsstrahlung has been measured for the first time from free atoms. The electron beam energy was 28 or 50 keV. The photon spectrum was detected at 90° to the incident electron beam. The cross section is differential with respect to photon energy and angle. The scattered electron is not observed, the spin polarization of the electron and photon is not observed, and the recoil target atom is not observed and is assumed to be left in the ground state.

Theory.—It was not until the 1990s that calculations of the photon spectrum over the whole energy range from a few keV up to the kinematic end point that included a PB contribution began to become available for targets and electron energies that are accessible to experiment. The extensive work of Korol, Solov'yov, and their co-workers for Cu and Ag [40], for Ar [41], and for Kr and Xe for 25 keV [42] was essential in the early stages of this experiment. These calculations provided the first theoretical estimates of the effect of PB on the total bremsstrahlung spectrum. The initial theoretical work was in the nonrelativistic Born approximation, but it demonstrated both the size of the expected contribution and some of the essential features of the photon spectrum, such as the increase of the cross section at lower photon energy, the structure at the characteristic absorption edges of the target atom, and the change in the slope of the spectrum at the absorption edges.

More recently, a calculation of the total bremsstrahlung spectrum including PB has been done in what is called the stripping approximation (SA). The original idea of the SA is due to Amusia *et al.* [43]. There have been two versions of the SA [44,45], and they have been shown to be equivalent [46]. We have used the SA formulation of Avdonina and Pratt [45] because its relative ease of implementation allowed us to obtain results for comparison with our experiment.

While the SA provides the photon energy spectrum, an additional approximation is necessary to obtain the angular distribution. We have used the OB tabulations [2] for an estimate of the shape function for the angular distribution. This approximation is likely to lead to an underestimate of the contribution of PB especially at higher electron energies. The shape function for PB is expected to be more dipolelike and peak at 90° while the shape function for OB is peaked at a more forward angle as the electron energy increases and thus is lower at 90°. Furthermore, the SA does not include interference between the OB and PB amplitudes. Interference is very important near the characteristic absorption edges of the target atom, but it may also be important at other photon energies. Thus while an accurate theory of OB exists for comparison with the experimental data, the presently available SA theory is only approximate. We have used the SA to suggest the trend of the effect of PB that may be expected from a more complete theory.

Experiment.—The experimental setup has been described in Ref. [47]. The electrons are accelerated by a Cockcroft-Walton accelerator and guided to a differentially pumped Al target cell. Photons were detected at 90° by a Si(Li) detector coupled to the target cell through a 0.005 08 mm thick Kapton window.

The absolute doubly differential cross section $\frac{d^2\sigma}{d\Omega dk}$ is determined from

$$N(k) = N_0 \tau \Delta\Omega \Delta k \varepsilon(k) a(k) \frac{d^2\sigma}{d\Omega dk} + \mathrm{TTB}(k) + B(k). \quad (1)$$

$N(k)$ is the number of counts at photon energy k, N_0 is the number of incident electrons, τ is the thickness of the gas target in atoms/cm^2, $\Delta\Omega$ is the solid angle subtended at the detector by the interaction region in the target, $a(k)$ is the absorption of the Kapton window, Δk is the width of the energy channel, and $\varepsilon(k)$ is the detector efficiency.

$\mathrm{TTB}(k)$ is the background due to thick target bremsstrahlung (TTB) produced by electrons that have elastically scattered into either the Kapton window or in the target cell wall and is discussed in detail in Ref. [48]. The TTB absolute yield was modeled [49–51] and the model was validated by comparison with absolute TTB yield measurements [51]. The geometry of the experiment was designed to minimize this background, and it was found to be negligible at energies above 15 keV and only 1% of the data at 5 keV. Finally, $B(k)$ is the background when the target gas is removed. $B(k)$ was measured in a separate target-empty run.

The measurement of each of the terms in Eq. (1) and the background corrections are discussed in Ref. [47] and the errors due to each term are summarized below.

Results and discussion.—The results are shown in Fig. 1 for 28 keV for Kr and Xe, in Fig. 2 for 50 keV for Kr and Xe, and in Fig. 3 for 50 keV for Ar and Ne. Preliminary results for Xe at 50 keV and Kr at 28 keV have been previously reported [47]. The characteristic x-ray peaks in the data have been omitted. The dashed curve is OB calculated from the tabulation in Ref. [2]. The solid curve is our calculation of the SA based on the formula in Ref. [47] and the shape function from OB [2]. The characteristic x-ray K and L absorption edges for the target atoms can be seen in the solid curve. The data have not been extended below about 5 keV because of increased uncertainty in the detector efficiency below this energy.

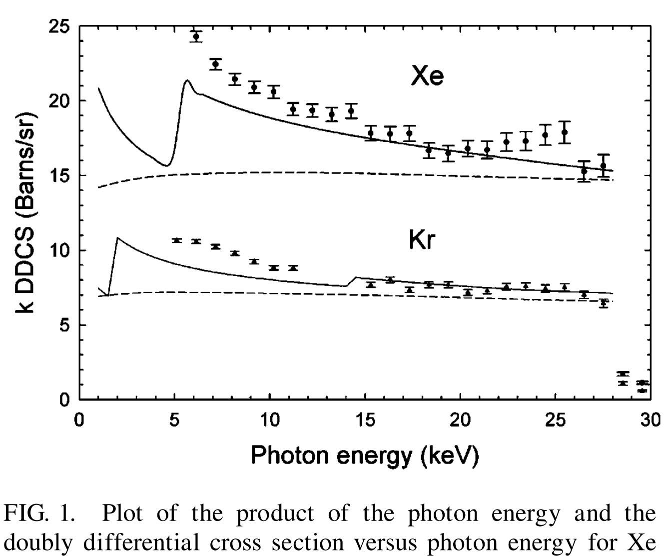

FIG. 1. Plot of the product of the photon energy and the doubly differential cross section versus photon energy for Xe and Kr for 28 keV. The solid curve is our evaluation of the stripping approximation [43] using the shape functions from Ref. [2]. The dashed curve is from the tabulation of ordinary bremsstrahlung [2]. The errors shown are statistical. In addition there is a systematic scale error of 3.8%.

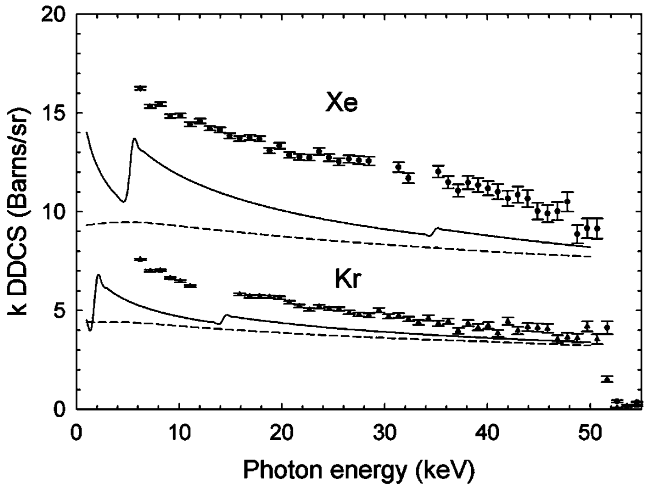

FIG. 2. Same as Fig. 1 except for 50 keV.

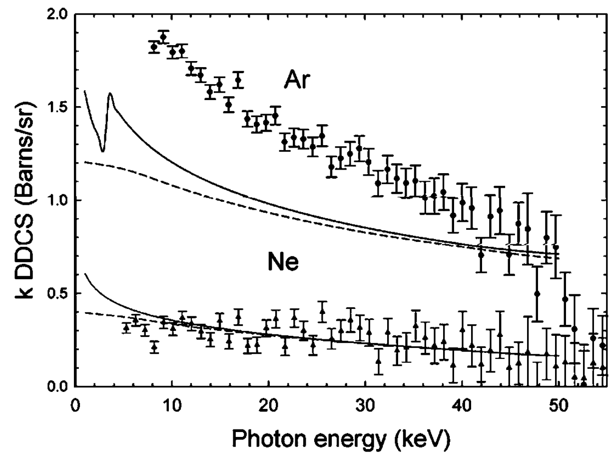

FIG. 3. Same as Fig. 1 except for Ar and Ne at 50 keV.

The errors shown are due to counting statistics in the data, corrected for backgrounds. In addition there is a systematic error on each plot that is due to the estimated errors in the target cell pressure ($\sim$1%), target cell temperature ($\sim$1%), effective target length ($\sim$1%), solid angle ($\sim$1%), charge collection ($\sim$1.5%), and efficiency ($\sim$2.8%). When these errors are combined in quadrature, the total systematic error is conservatively estimated to be $\pm$3.8%.

Overall the data at both 28 and 50 keV are higher than the prediction of OB. The data provide the first direct evidence that the contribution of PB in electron bremsstrahlung is important over the whole range of radiated photon energy. The absolute scale of the data is in reasonable agreement, within errors, with OB near the kinematic end point, but the discrepancy increases as the photon energy decreases. The data at 28 keV are in good agreement with the trend suggested by the SA. Considering that the SA curve is an underestimate because of the use of the OB shape function, the agreement suggests that interference effects may not be so significant at this energy. At 50 keV, the agreement with the SA model for Kr and Xe is not as good. Although the trend of the SA follows the data, the disparity in photon energy dependence is larger and suggests that the interference effects may be more important at higher energy. The use of the OB shape function at 50 keV is expected to result in poorer agreement between the SA scale and the data. The discontinuity in the SA curve at the characteristic x-ray absorption edges is not seen in the data. This is a further indication that the inclusion of interference is important.

In Fig. 3, the PB contribution for Ne seems to be small, and there is good agreement between the data and OB theory. The comparison between data and the SA for Ar is similar to that for Kr and Xe. The contribution of PB for Ar appears to be significant over most of the photon energy range. The SA model suggests the trend of the photon energy dependence but is not in good agreement in either shape or magnitude with the data.

Conclusions.—We have reported the first absolute doubly differential cross sections for electron bremsstrahlung from gas targets. The experiment is precise enough to provide the first evidence that the fully relativistic partial wave calculation of OB is not sufficient to describe the electron bremsstrahlung data over the whole range of radiated photon energy. While absolute agreement with OB theory is good at the kinematic end point, the data systematically diverge from the theory as photon energy decreases. This provides the first experimental evidence that PB is important over a wide range of radiated photon energy. The data have also been compared to a calculation of total bremsstrahlung in the SA that does not include interference between the OB and PB amplitudes. While the SA agrees with the trend of the data at both 28 and 50 keV, it does not agree well with the 50 keV data in either magnitude or photon energy dependence, suggesting that interference effects may be important at higher electron energy over a broad range of photon energy.

New calculations are needed for the angular distribution of electron bremsstrahlung for the relativistic case that includes PB and interference between the PB and OB amplitudes. Recently fully relativistic results have been presented for heavy projectiles [52,53], but calculations for electrons at the energy range of this experiment are not yet available.

Additional experiments are needed to provide a range of accurate benchmarks for the test of new theoretical models. Specifically, experiments are needed to (i) investigate more fully the complex dependence of the bremsstrahlung spectrum on photon energy and atomic number, (ii) investigate the spectrum at other photon angles, especially backward angles where the PB contribution may be relatively larger, and (iii) study the spectrum at higher electron energy where relativistic effects are more important.

The authors thank M. Ya. Amusia, Nina Avdonina, Andrey Korol, Andrey Lyalin, Oleg Obolenski, Richard Pratt, and Andrej Solov'yov for their interest and theoretical support during the course of this work. We also thank Mike Murdock and David Yale for constructing the target cells.

*Now at Sandia National Laboratories, MS 1193, Albuquerque, NM 87185-1193.

[1] H. K. Tseng and R. H. Pratt, Phys. Rev. A **3**, 100 (1971).
[2] Lynn Kissel, C. A. Quarles, and R. H. Pratt, At. Data Nucl. Data Tables **28**, 381–460 (1983).
[3] H. W. Koch and J. W. Motz, Rev. Mod. Phys. **31**, 920–955 (1959).
[4] R. H. Pratt and I. J. Feng, *Atomic Inner Shell Physics*, edited by Bernd Crasemann (Plenum Publishing Corporation, New York, 1985), Chap. 12, pp. 533–580.
[5] R. H. Pratt *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **99**, 156–159 (1995).
[6] S. M. Seltzer and M. J. Berger, Nucl. Instrum. Methods Phys. Res., Sect. B **12**, 95 (1985).
[7] M. Ya. Amusia, A. S. Baltenkov, and A. A. Paiziev, Pis'ma Zh. Eksp. Teor. Fiz. **24**, No. 6, 366 (1976) [JETP Lett. **24**, 332 (1976)].
[8] V. M. Buimistrov, Ukr. Fiz. Zh. **17**, 640 (1972).
[9] V. M. Buimistrov and L. I. Trakhtenberg, Zh. Eksp. Teor. Fiz. **69**, 108 (1975) [Sov. Phys. JETP **42**, 54 (1975)].
[10] B. A. Zon, Sov. Phys. JETP **46**, 65 (1977).
[11] M. Ya. Amusia, Phys. Rep. **162**, 5–249 (1988).
[12] *Polarization Bremsstrahlung of Particles and Atoms*, edited by V. N. Tystovich and I. M. Oiringel (Plenum Press, New York, 1992).
[13] A. V. Korol and A. V. Solovy'ov, J. Phys. B **30**, 1105–1150 (1997).
[14] C. A. Quarles and D. B. Heroy, Phys. Rev. A **24**, 48 (1981).
[15] R. Hippler, K. Saeed, I. McGregor, and H. Kleinpoppen, Phys. Rev. Lett. **46**, 1622 (1981).
[16] M. Semaan and C. A. Quarles, Phys. Rev. A **24**, 2280 (1981).
[17] M. Semaan and C. A. Quarles, Phys. Rev. A **26**, 3152 (1982).
[18] Lee Estep and C. A. Quarles, Physica (Amsterdam) **145C**, 369 (1987).
[19] R. Ambrose, J. C. Altman, and C. A. Quarles, Phys. Rev. A **35**, 529 (1987).
[20] V. Ambrose, C. A. Quarles, and R. Ambrose, Nucl. Instrum. Methods Phys. Res., Sect. B **124**, 457–463 (1997).
[21] R. J. Liefield, A. F. Burr, and M. B. Chamberlain, Phys. Rev. A **9**, 316 (1973).
[22] G. Wendin and K. Nuroh, Phys. Rev. Lett. **39**, 48 (1977).
[23] T. M. Zimkina, A. S. Shulakov, and A. P. Braiko, Sov. Phys. Solid State **23**, 1171–1173 (1981).
[24] T. M. Zimkina *et al.*, Sov. Phys. Solid State **26**, 1201 (1984).
[25] E. T. Verkhovtseva, E. V. Gnatchenko, and P. S. Pogrebnjak, J. Phys. B **16**, l613 (1983).
[26] E. T. Verkhovtseva *et al.*, Zh. Eksp. Teor. Fiz. **98**, 797 (1990) [Sov. Phys. JETP **71**, 443–4448 (1990).
[27] A. V. Korol, A. G. Lyalin, A. S. Shulakov, and A. V. Solovy'ov, J. Phys. B **28**, L155–L160 (1995).
[28] A. V. Korol, A. G. Lyalin, A. S. Shulakov, and A. V. Solovy'ov, JETP **82**, 631—637 (1996).
[29] A. A. Tkachenko, E. V. Gnatchenko, and E. T. Verkhovtseva, Opt. Sectrosc. (USSR) **78**, 183 (1995).
[30] E. V. Gnatchenko, A. A. Tkachenko, and E. T. Verkhovtseva, Opt. Spectrosc. (USSR) **92**, 17 (2002).
[31] K. Ishii and S. Morita, Nucl. Instrum. Methods Phys. Res., Sect. B **3**, 57–61 (1984).
[32] K. Ishii and S. Morita, Phys. Rev. A **30**, 2278 (1984).
[33] K. Ishii and S. Morita, Phys. Rev. A **31**, 1168 (1985).
[34] K. Ishii and S. Morita, Nucl. Instrum. Methods Phys. Res., Sect. B **22**, 68–71 (1987).
[35] K. Ishii *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **75**, 73–76 (1993).
[36] K. Ishii, Nucl. Instrum. Methods Phys. Res., Sect. B **99**, 163–165 (1995).
[37] K. Ishii *et al.*, Int. J. PIXE **9**, Nos. 1&2, 1–10 (1999).
[38] C. A. Quarles and S. Portillo, CP475, in *Applications of Accelerators in Research and Industry*, edited by J. L. Duggan and I. L. Morgan, (AIP, Woodbury, NY, , 1999), pp. 174–177.
[39] S. Klein, Rev. Mod. Phys. **71**, 1501–1538 (1999).
[40] A. V. Korol and A. V. Solov'yov (private communication).
[41] A. V. Korol, A. G. Lyalin, and A. V. Solov'yov, J. Phys. B **30**, L115–L121 (1997).
[42] A. V. Korol, A. G. Lyalin, O. I. Obolenskii, and A. V. Solov'yov, JETP **87**, 251 (1998); A. V. Korol, A. G. Lyalin and A. V. Solov'yov, Opt. Sectrosc. (USSR) **86**, 486 (1999); (private communication).
[43] M. Ya. Amusia, M. Yu. Kuchiev, A. V. Korol, and A. V. Solov'yov, Sov. Phys. JETP **61**, 224 (1985).
[44] A. V. Korol, A. G. Lyalin, and A. V. Solov'yov, in *Proceedings of the 21st International Conference on Physics of Electronic and Atomic Collisions, Sendai, Japan, 1999* (Book of Abstracts) (University of Electro-Communications, Tokyo, 1999), p. 240.
[45] N. B. Avdonina and R. H. Pratt, J. Phys. B **32**, 4261–4276 (1999).
[46] A. V. Korol, A. G. Lyalin, A. V. Solov'yov, N. B. Avdonina, and R. H. Pratt, J. Phys. B **35**, 1197–1210 (2002).
[47] S. Portillo and C. A. Quarles, CP 680, *Applications of Accelerators in Research and Industry*, edited by J. L. Duggan and I. L. Morgan (AIP, Woodbury, NY, 2003), p. 115–118; S. Portillo, Ph.D. dissertation, Texas Christian University, 2002 (unpublished).
[48] C. A. Quarles, *Accelerator-Based Atomic Physics: Techniques and Applications*, edited by S. M. Shafroth and J. C. Austin (American Institute of Physics, Woodbury, New York, 1997), Chap. 8.
[49] E. Storm, Phys. Rev. A **5**, 2328 (1972).
[50] V. Ambrose, C. A. Quarles, and R. Ambrose, Nucl. Instrum. Methods Phys. Res., Sect. B **124**, 457–463 (1997).
[51] M. Seeman and C. A. Quarles, X-Ray Spectrom. **30**, 37–43 (2001).
[52] A. V. Korol *et al.*, JETP **94**, 704 (2002).
[53] A. V. Korol, O. I. Obolenskii, A. V. Solov'yov, and I. A. Solovjev, J. Phys. B **34**, 1589 (2001).