1992

Density effect in Cu K-shell ionization by 5.1-GeV electrons

W. E. Meyerhof

D. G. Jensen

D. M. Kawall

S. E. Kuhn
Old Dominion University, skuhn@odu.edu

D. W. Spooner

See next page for additional authors

Original Publication Citation

Meyerhof, W. E., Jensen, D. G., Kawall, D. M., Kuhn, S. E., Spooner, D. W., Meziani, Z. E., & Faust, D. N. (1992). Density effect in Cu K-shell ionization by 5.1-GeV electrons. *Physical Review Letters, 68*(15), 2293-2296. https://doi.org/10.1103/PhysRevLett.68.2293

Authors

W. E. Meyerhof, D. G. Jensen, D. M. Kawall, S. E. Kuhn, D. W. Spooner, Z. E. Meziani, and D.. N. Faust

Density Effect in Cu K-Shell Ionization by 5.1-GeV Electrons

W. E. Meyerhof, D. G. Jensen, D. M. Kawall, S. E. Kuhn, D. W. Spooner, Z.-E. Meziani, and D. N. Faust
Department of Physics, Stanford University, Stanford, California 94305

(Received 16 January 1992)

We have made an absolute measurement of the Cu K-shell impact ionization cross section by 5.1-GeV electrons, which demonstrates directly a density effect predicted by Fermi in 1940. By determining the ratio of the K x-ray yield from a thin front and back layer of the target by a novel grazing emission method, we have verified the effect of transition radiation on the x-ray production, suggested by Sorensen and reported by Bak *et al.*

PACS numbers: 34.80.Dp

For many years, measurements of the impact ionization cross section by relativistic electrons [1] failed to find a reduction of the cross section predicted by Fermi in 1940 [2]. Fermi noted that the maximum impact parameter in an ionizing collision of a target electron by a relativistic charged particle is approximately given by $b_{\max} \simeq v\gamma/\nu$, where $v \simeq c$ is the velocity of the particle, $\gamma = (1-v^2/c^2)^{-1/2}$ is its Lorentz factor, and ν is the appropriate frequency of the electron [3]. In the present case, $\nu \simeq U_K/h$, where U_K is the K-shell binding energy. For large values of γ, $b_{\max}$ can extend over many layers of target atoms whose dynamic polarization reduces the time-varying electric field at the site of the active electron and, hence, the ionization probability. For Cu, at $\gamma = 10^4$, $b_{\max} \simeq 1.4$ μm. Bak *et al.* [4] were the first to note that in highly relativistic collisions the onset of this "density effect" is gradual as the ionizing particle penetrates the (solid) medium from the vacuum. Hence, for sufficiently thin targets no density effect is observed.

In more detail [5,6], the Fourier components of the electric field of the particle (and the associated virtual photons which ionize the medium) adjust from the vacuum value to the screened value within a formation zone whose (frequency-dependent) thickness is ~ 1 μm in the present experiment. As a result of the field adjustment, "transition radiation" (TR) photons are formed. These travel essentially along the beam direction and subsequently are absorbed photoelectrically in the medium with an absorption length $\lambda_a \simeq 3.8$ μm (3.4 mg/cm^2) near the K edge. (It is noted in Ref. [5] that the absorption takes place already in the formation zone.) For targets much thinner than λ_a, no density effect occurs. For targets much thicker than λ_a, the full density effect develops at the back of the target. In between these extreme cases, a partial density effect should be found.

Using Al and Cu targets thicker than λ_a, Bak *et al.* [4] could demonstrate a partial reduction of the K-shell ionization cross section. Furthermore, by adding, in front of the target, foils thin enough to avoid significant bremsstrahlung production, an enhancement of the cross section by the additional transition radiation was demonstrated [1]. On the other hand, a direct measurement of the difference between the x-ray intensity emitted by the front and the back of a thick target was only in fair agreement with theory, perhaps because of background effects or the statistical uncertainty of the results [1].

It occurred to us that a direct measurement of the K x-ray production near the front and back could be made even for foils as thin as a few μm, if one detects only those x rays which are emitted at grazing angles with respect to the target surfaces. The method is illustrated in Fig. 1(a). Defining the angle between the incident beam and the normal to the target foil as the "tilt angle" α, the K x rays produced at a distance z within the target along the beam direction can reach detector F (positioned at 90° to the beam, 11 m from the target) only after absorption by a factor $a_f = \exp(-\mu_K z \cot\alpha)$, where μ_K is the linear absorption coefficient for target K x rays. Hence, the *detected* x rays are produced in a surface layer of approximate thickness $\mu_K^{-1}\tan\alpha$, which for Cu lies between ~ 0.4 and ~ 2 μm (0.36–1.8 mg/cm^2) for α between 1° and 5°. Similarly, the x rays which reach detector B experience an absorption $a_b = \exp[-\mu_K(t-z)\cot\alpha]$, where t is the target thickness along the beam direction, and originate at the back of the target mainly also in a layer of thickness $\mu_K^{-1}\tan\alpha$.

From the expressions of Ref. [6] we have calculated the z dependence of the local K-vacancy production cross section σ_K in Cu for 5.1-GeV electrons [7]. The absolute counts in the detectors F and B, which we denote by F and B, and the ratio F/B are then computed for any target thickness and tilt angle from the relations

$$F = G\int_0^t \sigma_K a_f \, dz, \quad B = G\int_0^t \sigma_K a_b \, dz\,. \tag{1}$$

Here, G is a geometrical factor which consists of a product of the number of incident electrons, the number of target atoms per cm^3, the fluorescence yield, the solid angle of each detector divided by 4π, and the detection efficiency. The theoretical K x-ray intensities have to be corrected for beam-induced K-x-ray-producing backgrounds of which the major ones are bremsstrahlung [8] and knock-on electrons [9].

Before discussing the experimental arrangement and results, we present calculations for B and for F/B. The curves in Fig. 2 give the corrected back-face counts for the thickest target used by us (61 mg/cm^2 Cu, which should be enough to develop the full density effect); the

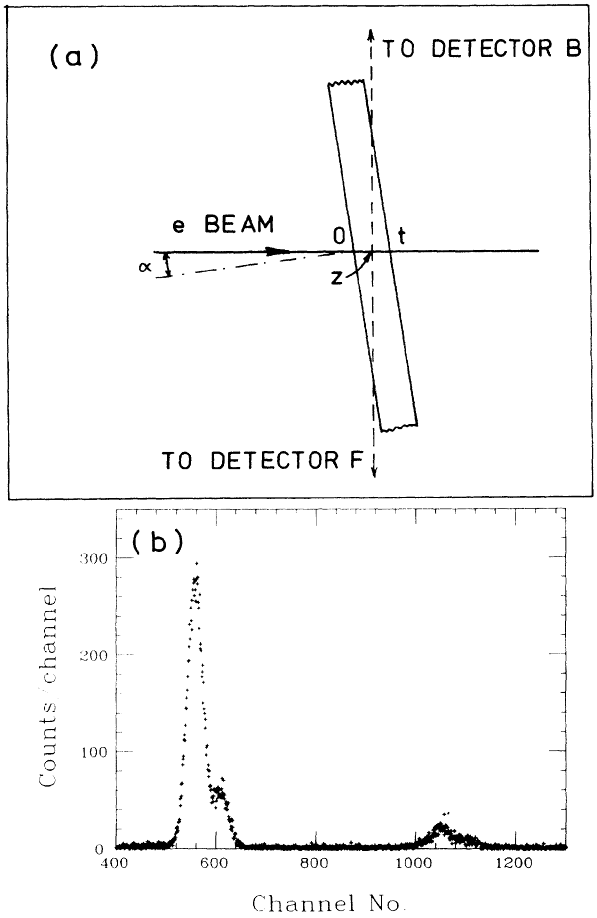

FIG. 1. (a) Principle of grazing emission method (not to scale). X rays produced at a distance z from the front face of the target foil must penetrate through a distance $z\cot\alpha$ before reaching the detector F, 11 m from the target. The x rays must penetrate a distance $(t-z)\cot\alpha$ to reach the detector B. (b) Typical Cu K (α and β) x-ray spectra from the detectors, gated with the beam pulse. At the higher channels, a double pileup peak can be seen.

corrections add less than 10% to the theoretically expected yields. The curves are derived from Eq. (1), assuming a fluorescence yield of 0.44 [10], a detection solid angle of 5.74×10^{-7} sr, an absorption correction for Be windows and air space (see below) of 0.971, and normalizing to $10^9 e$. The curves are shown for positive and negative values of α, corresponding to target orientations in which the back face of the target is seen by the detectors B or F, respectively. The solid curves in Fig. 3 give the theoretical F/B ratios for various Cu target thicknesses. The dashed curves have been corrected for the expected backgrounds. Here, the corrections for the thickest targets are substantial, because bremsstrahlung and knock-on electrons induce more K x rays towards the back of the target, whereas transition radiation induces more K x rays near the front.

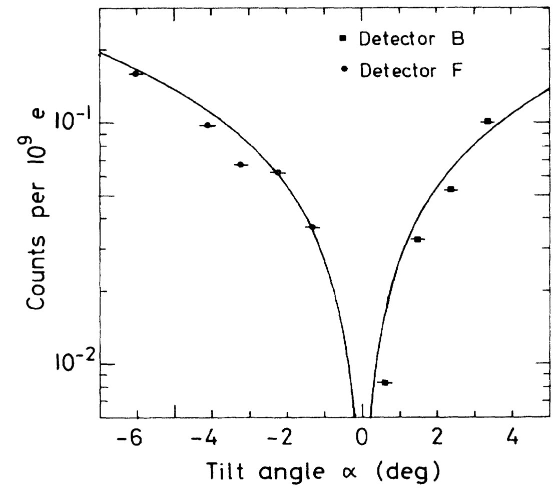

FIG. 2. K x-ray counts per $10^9 e$ from the back face of a 61-mg/cm^2 Cu target as a function of tilt angle α. The curves are computed from Eq. (1), using the calculations of Ref. [6] and include background corrections.

The experimental arrangement was relatively simple. Target foil strips, 9.3 mm wide and 46 mm long, were mounted on a ladder whose vertical stays were bent out of the way so that the detectors F and B had an unobstructed view of each target strip. A 5.1-GeV electron beam

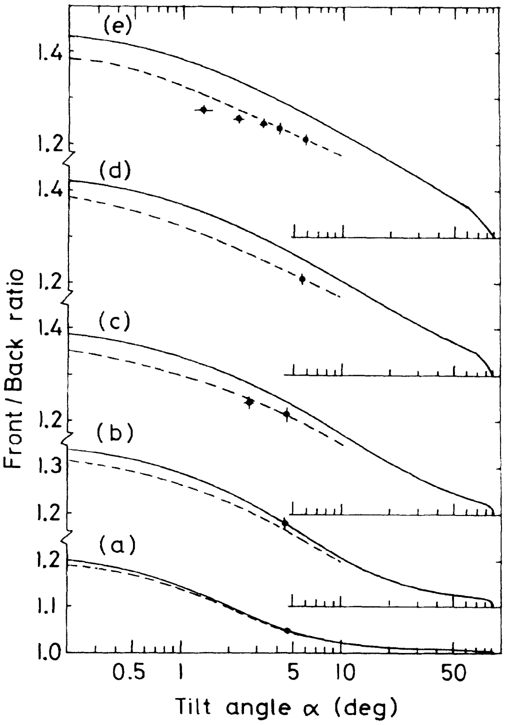

FIG. 3. Front- to back-face K x-ray counting ratios as a function of tilt angle for Cu foils of the following thicknesses: (a) 2.7, (b) 10.8, (c) 21, (d) 38, and (e) 61 mg/cm^2. The solid curves are computed from Eq. (1), using the calculations of Ref. [6]. The dashed curves are corrected for background-induced x rays, as described in the text.

from the Stanford Linear Accelerator Center was focused to a 3-mm-diam spot at the center of the target. The beam consisted of 0.5-μs-wide pulses at a repetition rate of 120 pulses/s. Typical beam intensities were $0.7\times 10^9 e$ per pulse at the larger tilt angles and up to $5\times 10^9 e$ per pulse for the smallest tilt angle. X rays were detected by two identical 200-mm^2 Si(Li) ORTEC x-ray detectors [11], collimated by 0.8-mm-thick lead collimators to an acceptance area of 70 mm ^{2} and placed at 11 m from the target. The detectors had 50-μm-thick Be windows. Each detector was shielded by a 0.9-m-thick concrete house. An evacuated beam pipe stretched from the target to within 1.5 cm of each detector window. Each pipe was sealed by a 25-μm-thick Be window.

The x-ray spectra were recorded in event mode, gated by 2-μs-long gates so that each beam pulse would fall within the center of the gate. Typically, the spectra had a few-percent background [Fig. 1(b)]. Despite the small solid angle subtended by the detectors, double pileup pulse-height peaks could be seen. The double pileup peaks were used to correct the single count peaks, assuming a Poisson distribution in the number of counts per beam pulse. Typically, between 0.05 and 0.15 count per pulse were detected. By moving the electron beam off the target strip with a weak-field magnet, we could show that external backgrounds, such as synchrotron radiation, were negligible.

The data points in Fig. 2 give the measured back-face counts for the 61-mg/cm^2 Cu target, corrected for pileup, and normalized to $10^9 e$. The statistical error on each data point is approximately 1% or less. The greatest uncertainty is produced by the setting of the tilt angle, which had to be done manually in this experiment. We assign an uncertainty of $\pm 0.2°$ to this setting. The zero position of the tilt angle could be determined only by fitting the entire set of points with the computed curves for positive and negative tilt angles. Data from tilt angles below 1° could not be trusted since surface unevenness of the electrolytically deposited foils [12] caused variations in α of the order of 0.5°.

The back-face counts for the 61-mg/cm^2 target, after background subtraction, are essentially due only to the electron impact ionization and not TR. Hence, one can use the data points for this target, as well as those for 38- and 21-mg/cm^2-thick targets (with small corrections), to compute the impact ionization cross section absolutely. We find a mean value of 378 ± 43 b. This can be compared to calculations, which include the density effect, by Scofield [13], Sorensen [6], and Chechin and Ermilova [7] of approximately 390 b. Without the density effect, the corresponding calculated cross sections lie between 540 and 580 b. Hence, our measurements provide, for the first time, an absolute confirmation of the density effect in inner-shell impact ionization by relativistic electrons.

Figure 3 gives the measured F/B ratios as a function of tilt angle. Whenever positive and negative tilt angles were within $\pm 0.2°$, we have averaged the F/B values. As the target thickness is reduced, F/B tends towards unity at the larger tilt angles. As noted at the beginning of this paper, for these targets one should measure essentially the "vacuum" cross section throughout the target [1,5,6]. As the target thickness increases, the theoretical F/B tends towards the expected ratio of $\sim 560/390 \simeq 1.44$ at the smaller tilt angles where the thin-layer front and back K x-ray yields are separately detected. On the whole, the measurements are in very good agreement with the background-corrected theoretical values. At the smallest tilt angles, the data points fall below the expected values. This could be due to the target surface unevenness and/or a slightly incorrect z dependence of the calculated backgrounds (or the theoretical cross sections). Efforts are presently under way to use an electron-photon transport code, EGS (electron-gamma shower) [14], to make more accurate background calculations. It is clear from the data, though, that transition radiation has an important effect on inner-shell K-vacancy production near the front face of the target, as suggested by Bak *et al.* [1,4] and supported by theory [6,7].

We are very grateful to A. H. Sorensen for suggesting a reinvestigation of the density effect in impact ionization by relativistic electrons. Useful and encouraging discussions with H. Genz are gratefully acknowledged. The competent programming of the expressions of Ref. [6] by Andrew Lee is very much appreciated. Our deep thanks go to the staff of SLAC for providing excellent technical assistance and to the administration of SLAC for granting a 24-h beam period, which made this experiment possible. This work was supported in part by National Science Foundation Grant No. PHY-9019293 (Stanford University) and by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the Department of Energy, under Contracts No. DE-AC03-76SF00515 (SLAC) and No. DE-FG03-88ER40439 (Stanford University).

---

[1] A list of references can be found in J. F. Bak *et al.*, Phys. Scr. **33**, 147 (1986).

[2] E. Fermi, Phys. Rev. **37**, 485 (1940).

[3] *Nuclear Physics, a Course Given by Enrico Fermi at the University of Chicago*, compiled by J. Orear, A. H. Rosenfeld, and R. A. Schluter (Univ. Chicago, Chicago, 1950), Sec. IIA.

[4] J. F. Bak *et al.*, Phys. Rev. Lett. **51**, 1163 (1983).

[5] A. H. Sorensen and E. Uggerhoj, Comments At. Mol. Phys. **17**, 285 (1986).

[6] A.H. Sorensen, Phys. Rev. A **36**, 3125 (1987).

[7] The results of V. A. Chechin and V. K. Ermilova, Z. Phys. D **13**, 33 (1989), agree within a few percent with

those of Ref. [6].

[8] Y. S. Tsai, Rev. Mod. Phys. **46**, 815 (1974).

[9] J. M. Jauch and F. Rohrlich, *The Theory of Photons and Electrons* (Springer, New York, 1975), Chap. 12. To compute the induced x-ray yield, we used parametrizations of the electron K-shell impact ionization cross section at low and high energies by J. Lennon *et al.*, J. Phys. Chem. Ref. Data **17**, 1285 (1988), and by H. Genz, Comments At. Mol. Phys. **14**, 173 (1984), respectively. The constants were adjusted to fit Ni data from threshold to 1 GeV [S. M. Seltzer, in *Monte Carlo Transport of Electrons and Photons*, edited by T. M. Jenkins, W. R. Nelson, and A. Rindi (Plenum, New York, 1988), p. 81, Fig. 4.20]. The resulting formula was extrapolated to Cu.

[10] W. Bambynek *et al.*, Rev. Mod. Phys. **44**, 716 (1972); H. Genz *et al.*, Z. Phys. A **305**, 9 (1982), have questioned whether particle energy and electric polarization of the target could affect the fluorescence yield. Direct calculations have not been made, as far as we are aware, but we note that the Cu fluorescence yield ω_K is remarkably insensitive to the number of M vacancies [R. S. Fortner *et al.*, J. Phys. B **5**, L73 (1972)]. For up to 6 M vacancies, ω_K varies by less than 10%. This shows that large variations of the electric field over the atomic volume of Cu do not have an appreciable influence on ω_K.

[11] We are very grateful to J. Tanis for the loan of one detector.

[12] Obtained from Chromium Corporation, Cleveland, Ohio 44105. By weighing and measuring, we found the density of these foils to be approximately 10% less than the full density. Hence we specify the foil thickness in mg/cm^2 rather than in μm.

[13] J. H. Scofield, Phys. Rev. A **18**, 963 (1978).

[14] W. R Nelson, H. Hirayama, and D. W. O. Rogers, *The EGS4 Code System* [Stanford Linear Accelerator Center Publication, SLAC-25, 1985 (unpublished)].