Absolute C K x-ray production cross sections for 0.29–16.0-MeV protons on thin carbon foils

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Absolute carbon K x-ray production cross sections (σ_{Kx}) have been measured for 0.29–16.0-MeV protons on thin carbon foils, covering the region below the maximum in σ_{Kx} up to the high-velocity region described by asymptotic (Bethe) theory. An experimental fluorescence yield value $\omega_K = (2.46 \pm 0.35) \times 10^{-3}$ was determined for carbon. Experimental values of σ_K are compared to the BEA, SCA, PWBA, and asymptotic theory predictions. At energies close to the maximum in σ_K (~ 0.5 MeV) the BEA predictions were in good agreement with experiment, while at higher energies the PWBA predictions gave the best agreement. Predictions of asymptotic theory lay somewhat below experiment. The measurements show the predicted $(\ln E)/E$ dependence at higher energies, and experimental values for the two main parameters of the asymptotic theory, viz., $M^2_{\text{tot}} = 0.87$ and $C_{\text{tot}} = 8.5$ (both $\pm 20\%$) were derived from a fit to the data. These values are the first of their kind determined by ion bombardment.

I. INTRODUCTION

Considerable experimental effort in recent years has provided a broad range of K x-ray production cross-section (σ_{Kx}) measurements for proton and heavier-ion beams on targets ranging from Be to U.[1] In general, these measurements involve the region of σ_{Kx} from just above the maximum in the Coulomb ionization cross section (where projectile velocity, $V \approx V_K$, the average electron velocity in the K shell) down to projectile energies where possible quasimolecular effects are important. Very little work has been reported, however, on K-shell ionization by projectiles with $V \gg V_K$. The importance of measurements in this regime is due to the resulting simple asymptotic form of theoretical K-shell ionization cross sections (for structureless projectiles) and a consequent relatively direct method for determining the dipole matrix elements of the ionization (plus excitation) process.[2,3] The experimentally determined dipole matrix elements in turn permit deduction of oscillator strengths and other salient features of the atomic transitions involved.

Previous measurements[4,5] of σ_{Kx} for low-Z elements have been performed for proton velocities below the asymptotic region. In some cases, thick targets were used (necessitated by the use of low-efficiency detectors) which introduce additional experimental uncertainties due to the need for proton energy-loss (dE/dX) corrections. In this work we report measurements of σ_{Kx} for 0.29–16.0-MeV protons on thin carbon foils using a high-efficiency thin-window proportional counter. The present work gives the first complete set of relatively accurate (thin target) carbon σ_{Kx} measurements from moderately low proton velocities ($V < V_K$) to the high-velocity regime ($V \gg V_K$) described by the asymptotic (Bethe) theory.

II. EXPERIMENTAL PROCEDURE

The carbon K x-ray yield measurements were performed using proton beams from three linear accelerators: (i) between 0.29 and 1.02 MeV, the Rutgers-Bell 2-MeV Van de Graaff; (ii) between 1 and 3 MeV, the East Carolina University TTT-2 tandem Van de Graaff; and (iii) between 2 and 16 MeV, the Rutgers-Bell FN tandem Van de Graaff. The targets were 20–50-$\mu g/cm^2$ self-supporting C foils mounted on Al target frames at angles of 30° or 45° to the proton beams. Target thicknesses were measured by comparison of elastic-p scattering with that from a target of known thickness. The detector used for all measurements was a side-window cylindrical-geometry gas-flow proportional counter with a ~3000-Å Parylene-C window sandwiched between 82%- and 97%-transparent Ni mesh. Window transmission (45%) was measured directly by constructing a duplicate window with all the same materials and inserting it between the target and detector. A sample spectrum taken at $E_p = 6.0$ MeV is shown in Fig. 1 along with a graph of the relative detection efficiency as a function of gas (90% argon–10% methane) pressure to ascertain the importance of window effects and to check that C K x rays were being completely stopped in the detector. All measurements were

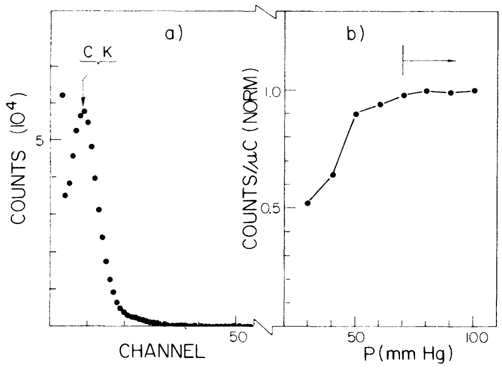

FIG. 1. (a) Gas-flow proportional-counter spectrum taken at $E_p = 6.0$ MeV; (b) C K x-ray peak intensity as a function of P-10 pressure.

made with a detector gas pressure of 70–80-mm Hg. Detector geometry was somewhat different for each accelerator but all measurements were made at 90° to the beam direction at distances varying from 16.5 to 35.5 cm. Proton-beam currents ranged from 2 to 8 nA and the counting rate in the proportional counter never exceeded 1 kHz and dead-time losses never exceeded 3%.

Considerable care was taken to minimize carbon accretion on the target by maintaining good vacuum $[(\sim 5-10)\times 10^{-7}$ Torr$]$ and by scattering the measurements so that certain energy points were repeated at intervals throughout the course of these measurements: e.g., the point at 8 MeV was repeated eight times as well as being the first and last points taken on the FN tandem run. Closely spaced points were reproducible to within 5% and maximum C buildup in any single accelerator run was a 5% increase, and corrections were made for the observed accretion.

In general, the peaks in the proportional-counter spectra were slightly asymmetric and incompletely resolved from noise. Peak intensities were obtained by summing from the center of the peak up to the background on the high-energy side (after subtracting a flat background). This technique was quite reproducible and gave good agreement with the intensity obtained by least squares fitting a Gaussian curve over the region of the peak just below the maximum on the low-energy side up to the background on the high-energy side. The background was less than 1% of the peak height for beam energies of 14 MeV and less. At higher energies, γ rays from proton-induced nuclear reactions in the Faraday-cup beam stop caused a noticeable increase in the background, thereby reducing the reliability of the peak intensity determination.

Overall the measurements of σ_{Kx} are estimated to have an absolute accuracy of ±20% (except for the 15- and 16-MeV points, which are ±25%). The error is calculated from the quadratic combination of the following errors: solid angle, 7%; target thickness, 7%; target self-absorption, 2%; absolute photopeak intensity determination, 15%; window absorption, 7%; charge collection, 2%; and target angle, 3%.

III. RESULTS AND DISCUSSION

The observed K x-ray yields Y_{Kx} were calculated directly from the observed intensities N_{obs} using

$$Y_{Kx} = N_{obs}/A\epsilon Q t\,\Delta\Omega\,, \qquad (1)$$

where A is the correction for absorption in the target and detector window, ϵ is the photopeak detection efficiency (here assumed to be 1), Q is the collected charge, t is the target thickness, and $\Delta\Omega$ is the solid angle subtended by the proportional counter. The maximum average proton energy loss in the target was about 5 keV (at 0.29 MeV) and was disregarded; i.e., no stopping power corrections were employed. The total x-ray production cross section σ_{Kx} is then just

$$\sigma_{Kx} = 4\pi Y_{Kx} \qquad (2)$$

and the total ionization (plus excitation) cross section σ_K is

$$\sigma_K = \sigma_{Kx}/\omega_K\,, \qquad (3)$$

where ω_K is the fluorescence yield. The experimental results for σ_{Kx} are listed in Table I. These

TABLE I. C K x-ray production cross sections. Errors ±20% except 15 and 16 MeV, which are ±25%.

E_p (MeV)	σ_{Kx} (kb)
0.29	2.21
0.52	2.80
0.72	2.77
1.02	2.45
2.00	2.01
3.00	1.46
4.00	1.23
5.00	1.08
6.00	0.93
7.00	0.83
8.00	0.81
9.00	0.72
10.00	0.67
11.00	0.65
12.00	0.63
13.00	0.55
14.00	0.53
15.00	0.53
16.00	0.58

absolute K x-ray production cross-section measurements agree with previous experimental results[1,4,5] within stated errors in their respective regimes of proton energy overlap.

Recent measurements by Toburen[6] (of Auger-electron yields) for 0.32–2.0-MeV protons on various C-containing gases provide values of σ_K in a proton energy region overlapping that of the present measurements. Calculation of ω_K at common energies in this region [using Eq. (3)] indicated that ω_K does not depend on beam energy in this region, in agreement with the results of Langenberg and Van Eck.[5] This is shown in Fig. 2. Hence we have calculated an averaged value of $\omega_K = (2.46 \pm 0.35) \times 10^{-3}$ (which is taken to be constant over the entire energy range of the present measurements) from our work in combination with that of Toburen. This agrees quite well with the value of 2.2×10^{-3} of Langenberg and Van Eck,[5] derived in a similar manner, but disagrees with experimental values of $(1.13 \pm 0.24) \times 10^{-3}$ (Dick and Lucas[7]), $(1.30 \pm 0.39) \times 10^{-3}$ (Feser[8]), and $(3.5 \pm 0.35) \times 10^{-3}$ (Hink and Paschke[9]). This experimental value is in good agreement with the theoretical prediction $\omega_K = 2.6 \times 10^{-3}$ of McGuire.[10] However, it should be noted that this value of ω_K does not necessarily represent an accurate measurement for solid carbon since the values of σ_K measured by Toburen were slightly sensitive to the type of gas used, indicating possibly a similar variation in σ_K for solid C.

The theoretical predictions of σ_K in the asymptotic region can be written[3] very simply as

$$\sigma_K = \frac{8\pi a_0}{\theta} \frac{Z_1^2}{Z_2^4} \frac{1}{(T/R)} \{M_{\text{tot}}^2[\ln(\gamma^2) - \beta^2] + C_{\text{tot}}\}, \tag{4}$$

where Z_1 and Z_2 correspond to the projectile and (screened) target Z, respectively, T is the projectile's kinetic energy times m_e/M_1, R is the binding energy of the C K electron [the ratio T/R can also be written as E_p(in MeV)/(0.52 MeV), i.e., the square of the projectile velocity in units of target-atom K-shell Bohr velocity], θ (=0.64 for C) is a screening constant defined as the ratio of the experimental C K-shell binding energy to the hydrogenic C K-shell binding energy, $\gamma^2 = \beta^2/(1-\beta^2)$, and $\beta_p = v/c$. The quantity M_{tot}^2 is the sum of the dipole matrix elements squared for ionization *and* excitation,[11] and C_{tot} is a parameter associated with energy transfer during the collision.[3]

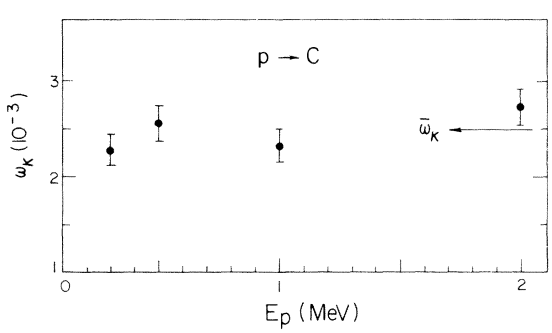

FIG. 2. Values of ω_K ($=\sigma_{Kx}/\sigma_K$) derived from this work (σ_{Kx}) and Ref. 9 (σ_K). Error bars shown include relative errors (5% for both σ_{Kx} and σ_K) only, not errors in absolute values of σ_{Kx} and σ_K.

The relation for σ_K includes significant excitation contributions ($n = 1 \to n = 2, 3, \ldots$) in addition to ionization since M_{tot}^2 involves the summation over all excited states plus integration over the continuum. Since the $2p$ shell of C is only partly filled and the $n = 1 \to n = 2$ excitation dominates the excitation contribution, we have corrected the hydrogenic dipole matrix elements in a statistical way by multiplying M_2^2 by $\frac{2}{3}$ and then including this corrected value in the sum for M_{tot}^2. In Fig. 3 are shown the predictions of the asymptotic theory and a comparison with the experimental values of $\sigma_{Kx}(\omega_K = 2.46 \times 10^{-3})$. Also shown are predictions of the binary-encounter approximation (BEA),[12] the plane-wave Born approximation (PWBA),[13] and the semiclassical approximation (SCA).[14] The BEA results are scaled[1] by $1/E$ from the highest-energy tabulated value, while the PWBA results are from the tabulated results of Khandelwal, Choi, and Merzbacher[15] which have been extended to higher energies.[16]

In the region close to the maximum in σ_{Kx} (about 0.5–0.6 MeV), the BEA theory is in excellent agreement with experiment but at the highest energies it falls about a factor of 2 below the data, clearly indicating that the $1/E$ dependence of this theory at energies considerably above the maximum in σ_{Kx} does not reproduce experimental re-

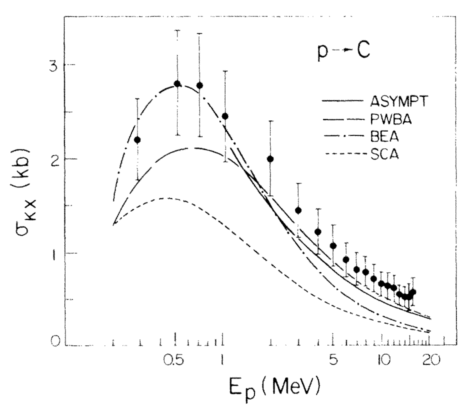

FIG. 3. CK x-ray production cross section as a function of proton energy: experimental points from this work, theoretical curves from references in text. A value of $\omega_K = 2.46 \times 10^{-3}$ has been used in the comparison.

sults. The SCA predictions lie consistently almost a factor of 2 below the data, and do not agree with the PWBA predictions except at 0.1 MeV (where it crosses the PWBA curve). The PWBA predictions lie slightly below the data over the whole range of energies, but generally within experimental error. Asymptotically the PWBA predictions must coincide with the predictions of the asymptotic theory and must in particular display the $(\ln E_p)/E_p$ dependence at energies considerably above the maximum in σ_{Kx}. The asymptotic theory falls somewhat below all the points between 2 and 15 MeV, but gives a good representation of the relative shape of the data over the region.

The analytic form of Eq. (4) for σ_K suggests an exceptionally clear way of presenting asymptotic-region cross-section data, since (as first pointed out by Fano[17]) a plot of $(T/R)\sigma_K/8\pi a_0^2(Z_1^2/Z_2^4)$ vs $\ln(\gamma^2)-\beta^2$ will be a straight line. In addition, the slope of this line will be M_{tot}^2/θ, which provides experimental values of M_{tot}^2 (or for equivalent excitation/ionization matrix elements in cases where these can be separated). This straight-line behavior (expected on general theoretical grounds) is also a rigorous check on the reliability of the data. The experimental data are shown on this type of Fano plot in Fig. 4 along with the asymptotic-theory predictions [scaled from hydrogen (corrected)]. Also shown are the experimental relative x-ray production cross sections of Burch[18] for protons on C, normalized to Auger-electron measurements[6] as here. The agreement in σ_K between experiments is good at proton energies of 14 MeV or less, while above this point they appear to diverge somewhat. Combining the data sets (weighted according to stated uncertainties) and doing a linear least-squares fit on the data from 10 to 18 MeV gives $M_{tot}^2=0.87$. The error in this value is essentially the error in values of σ_K used in the fit, i.e., $\pm 20\%$. Improved accuracy in values of M_{tot}^2 rests directly on improving the measurements of σ_K (for Auger-electron measurements) or σ_{Kx} and ω_K (for x-ray measurements).

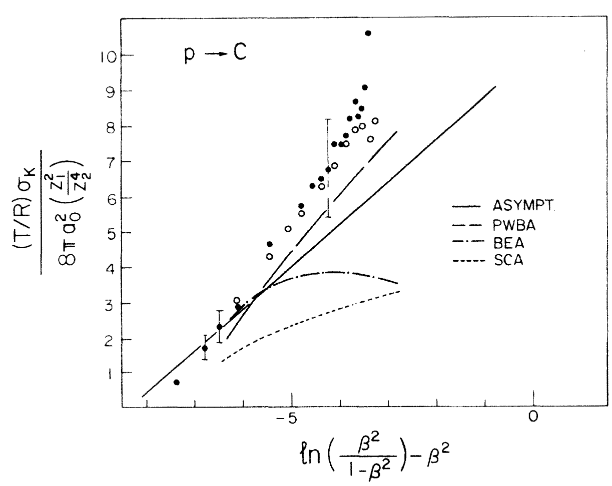

FIG. 4. Fano plot of "reduced" ionization cross section vs $\ln\gamma^2-\beta^2$. A "screened" $Z_2=6-0.3=5.7$ has been used in computations. The open circles are the normalized data of Burch. Also shown for comparison are the SCA, BEA, and PWBA predictions.

The other main parameter in the asymptotic theory is C_{tot}. C_{tot} is evaluated directly as the intercept at $\ln\gamma^2-\beta^2=0$ ($\beta=0.8118$). The fit results give $C_{tot}=8.5$ ($\pm 20\%$). These results are to be compared with the (uncorrected) hydrogenic values,[19] $M_{tot}^2=1.00$ and $C_{tot}=11.7$. These theoretical values for hydrogen, corrected for carbon in the manner discussed previously, give $M_{tot}^2\approx 0.81$ and $C_{tot}\approx 9.5$, which lie within the stated experimental errors.

Measurements of σ_K in the asymptotic region are quite common using electrons as projectiles. Values for the parameters of the Bethe theory are now readily available[20] from these electron impact measurements. Values of $M_{tot}^2=0.887\pm 0.004$ and $C_{tot}=9.53\pm 0.15$ (uncertainties are from the fit only and do not reflect actual experimental uncertainties) were derived by Powell[20] from experimental measurements by Glupe and Mehlhorn[21] for electrons on carbon. These values are in good agreement with our experimental results, also.

The agreement between experiment and theory is possibly fortuitous since (i) the data might not lie far enough into the asymptotic region, (ii) ω_K may vary over the 10–18-MeV range and be different from the value determined between 0.3 and 2 MeV, and (iii) carbon is not really "hydrogenic." Commenting on each of these in turn: (i) Electron impact measurements[4,20] on a wide range of targets from He to Cu show quite linear behavior in Fano plots for projectile-velocity/K-shell-electron-velocity ratios equivalent to those covered in this experiment even in the presence of exchange and Coulomb effects, which have little or no significance in this experiment. Also measurements[22] of σ_{Kx} for protons on carbon at energies beyond the range covered in this experiment give results for M_{tot}^2 and C_{tot} which are in excellent agreement with these values. (ii) Variations in ω_K (due to multiple ionization/excitation configurations) are probably not important in this experiment, since it has been noted[23] that multiple ionization is far more significant at low proton energies (< 100 keV) than at 0.5 MeV, where it has been observed to approach a constant value close to that expected from shakeoff. The results of Ref. 5 and this work both indicate no significant changes in ω_K in this energy region, hence the expectation that ω_K really is relatively constant above 0.5 MeV. (iii) The assumption that carbon is hydrogenic is weakened by the fact that the measurements employed solid carbon targets and hence solid-state effects could affect the dipole matrix elements. However, since our values for σ_K ultimately rest on the Auger measurements (with gas targets), solid effects are probably normalized out.

Our results show that the simple analytic form of the Bethe (asymptotic) cross section gives a good representation of relative experimental intensities in the region where it is applicable. In particular, the linear behavior of the data (on the Fano plot) is well described by the $(\ln E)/E$ dependence of the Bethe theory. The fact that the Bethe theory underestimates the absolute cross sections as presented here is possibly due to the fact that it has not been "scaled" quite properly. The values for M^2_{tot} and C_{tot} which have been determined here for the first time using ion bombardment are of the same order of accuracy as for electron bombardment. Clearly more accurate and systematic measurements will be required to determine values for these parameters that would provide substantive information on generalized oscillator strengths for comparison with theoretical values.

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