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Absolute C K x-ray production cross sections for 18–26-MeV protons on thin carbon foils*

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Absolute C K x-ray production cross-section measurements using 18–26-MeV protons on thin carbon foils extend the range of previous measurements in the asymptotic region. These measurements permit extraction of the two main parameters of the asymptotic theory, viz., $M^2_{\text{tot}} = 0.84$ and $C_{\text{tot}} = 8.2$, which are in good agreement with those obtained in previous work at lower energies. The ionization cross sections extracted from these measurements are compared with the predictions of the asymptotic theory as well as the binary-encounter, semiclassical, and plane-wave Born approximation theories.

Recently some of us reported on measurements of absolute C K x-ray production cross sections, σ_{Kx}, with protons of 0.29–16 MeV on thin C foils.[1] One of the main purposes of this experiment was to observe whether the ionization cross sections σ_K derived from these measurements would show the expected asymptotic behavior[2,3] at the highest energies [viz., an $(\ln E)/E$ dependence] which would permit extraction of the two main parameters of the asymptotic theory for the first time, using heavy ($m \gg m_e$) structureless projectiles, where Coulomb deflection and exchange effects are minimized or eliminated. It was difficult from the data to determine if the asymptotic region had been reached since it appeared approximately linear (on a Fano plot) over the whole energy range. The highest energy points were somewhat arbitrarily considered to lie in this asymptotic region and fits were made on that basis. In this work we report the results of measurements up to 26 MeV which confirm the results achieved in the earlier experiment and extend the range of these measurements.

A series of runs was made over the energy range 3–15 MeV using 1–10-nA proton beams from the Triangle Universities Nuclear Laboratory (TUNL) FN tandem van de Graaff. A second series of runs from 18–26 MeV was done using the TUNL cyclo-Graaff.[4] Normalization of the 18–26-MeV data to the previous lower-energy work was done. Considerably improved shielding was used to reduce the exponentially increasing nuclear-event associated background produced at these higher energies. At least 10 cm of lead shielded the detector from x and γ radiation in all directions from which background radiation could come. In addition paraffin shielding was placed around the detector to reduce neutron background. The beam was focused, so that more than 99% passed through a 3-mm aperture which was located just before the C target. The aperture was removed before x-ray data was taken. The spectra observed at the higher proton bombarding energies required more accurate, reliable ways of subtracting background from under the C K peak, hence separate runs were made with bare target frames (all other conditions the same). A functional form (exponential plus flat background) fit to this background spectrum was normalized to the peak-plus-background spectrum in the highest photon energy region and subtracted from the spectrum.

The measured x-ray yields were used to calculate σ_{Kx} for $E_p = 18–26$ MeV. These values of σ_{Kx} are given in Table I. For comparison with theoretical predictions, K-shell ionization cross sections were calculated from these values of σ_{Kx} using an experimental value for the fluorescence yield, $\omega_K = 2.46 \times 10^{-3}$, derived from previous work.[1] In Fig. 1 are shown the experimental values of σ_K compared with predictions of the binary encounter (BEA),[5] semiclassical approximation (SCA),[6] plane-wave-Born approximation (PWBA)[7,8] and asymptotic[3] theories for protons on carbon. Also

TABLE I. C K x-ray production cross sections. Errors ±20%.

E_p (MeV)	σ_{Kx} (kb)
18.00	1.74
19.00	1.54
20.00	1.50
21.00	1.46
22.00	1.38
23.00	1.34
24.00	1.26
25.00	1.26
26.00	1.26

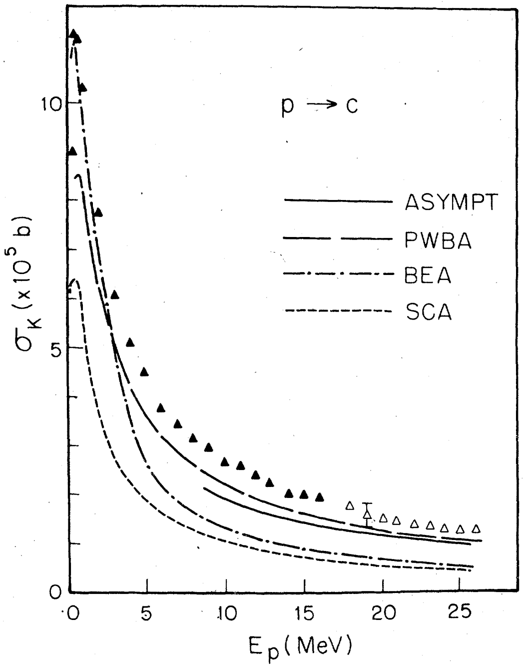

FIG. 1. σ_K vs Ep for p C. Data: ▲, are averaged values from Ref. 1, 9 and this work; △, this work.

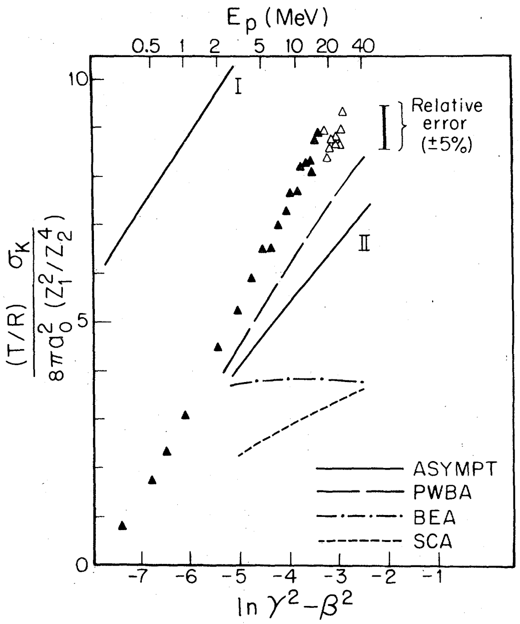

FIG. 2. Fano plot of data from Fig. 1. A "screened" $Z = 6 - 0.3 = 5.7$ has been used in computations. Asymptotic curve labeled I is hydrogenic case, II is the "corrected" hydrogenic case.

included are the weighted averages of previous measurements,[1,9] of σ_K from 0.29 to 18 MeV derived from x-ray yield measurements (plus the present normalized low-energy measurements). The asymptotic predictions have been scaled from the hydrogenic case as described in Ref. 1, and include a statistical correction for the partial filling of the carbon $2p$ shell, which reduces the excitation contribution to the asymptotic prediction. A more rigorous comparison of experiment with theory in the asymptotic region is obtained using a Fano plot as shown in Fig. 2. This type of plot takes advantage of the analytic form for σ_K in the asymptotic theory, viz.,

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

to present the cross-section data in a reduced form. Z_1 and Z_2 correspond to the projectile and (screened) target, T is the projectile's kinetic-energy times m_e/M, R is the binding energy of the CK electron, $\theta = 0.64$ is the screening constant, $\gamma^2 = \beta^2/(1-\beta^2)$, M_{tot}^2 is the sum of the matrix elements for ionization and excitation, and C_{tot} is a parameter associated with energy transfer during the collision.

When $(T/R)\sigma_K/8\pi a_0^2(Z_1^2/Z_2^4)$ is plotted against $\ln\gamma^2 - \beta^2$, the data should fall on a straight line whose slope is M_{tot}^2/θ and intercept [at $\ln\gamma^2 - \beta^2 = 0$] is C_{tot}/θ. A linear least-squares fit to the data from 18–26 MeV gives the values $M_{\text{tot}}^2 = 0.84$ and $C_{\text{tot}} = 8.2$ (both ±20%), in good agreement with previous work (see Table II). It is not possible to improve absolute accuracies for these values with

TABLE II. Comparison of M_{tot}^2 and C_{tot}.

Projectile	M_{tot}^2	C_{tot}	v_p/v_k	Reference
p	0.84[a]	8.2[a]	~6.7	This work
p	0.87[a]	8.5[a]	~4.8	1
e	0.887[b]	9.53[c]	~4	11, 12
Theory	1.00	11.7	•••	13 hydrogenic
Theory	0.81	9.5	•••	1 "corrected" hydrogenic

[a] Errors ±20%.

[b] Errors of ±0.5% from fit to data only (Ref. 12).

[c] Error of ±1.5% from fit to data only (Ref. 12).

x-ray measurements since ultimately comparisons between experimental and theoretical values for σ_K rest on Auger electron measurements of these quantities, which all have accuracies of no better than ± 15%.

Rcently Anholt *et al.*[10] have published results for measurements of 4.88-GeV protons on elements from Ni to U. In the case of Ni $v_1/v_K = 5$, whereas in our case for 26-MeV protons on C, $v_1/v_K = 7.1$. In addition to the "static" Coulomb interaction, they propose a "current-current" interaction at these high proton velocities ($\beta \approx 0.92$), which adds a contribution that varies as $\ln\gamma^2$ to the asymptotic cross section (where the Coulomb contribution varies as $\ln\gamma^2/E$). For this experiment (where $\beta^2 \approx 0.05$) the "current-current" interaction should contribute less than 0.1% to σ_k and has been disregarded.

The theoretical predictions that come closest to the 18–26-MeV data are those of the PWBA. The BEA predictions, which agree quite well with the lowest energy data, indicate a $1/E$ dependence of σ_k at the higher energies and are low by a factor of ~ 2.5 at 26 MeV.

In conclusion, we have measured σ_{Kx} for C with protons of 18–26 MeV, extending these measurements even further into the asymptotic region. Values of M^2_{tot} and C_{tot} derived from this work are in good agreement with those derived from the lower-energy measurements. This indicates that fairly reliable estimates of the main parameters of the asymptotic theory can be made at values of $v_1/v_K \geq 5$.

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