New Experimental Investigations of the Density Effect on Inner-Shell Excitation and Energy Loss

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The large spread in γ values (1–10^5) for gigaelectronvolt secondary beams has been used in a novel technique to measure the relativistic effects on inner-shell excitation in Cu and Al and energy loss in Si and Ge. In K-shell excitation, a pronounced influence of density effect is found for the first time, in apparent contradiction to earlier measurements, where the lack of density effects has been a great mystery. These problems are explained as target-thickness effects in connection with transition radiation.

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The energy loss of charged particles penetrating condensed materials at moderate relativistic energies is well described by the Bethe-Bloch formula. In a classical impact-parameter description, the average energy loss is roughly proportional to the logarithm of the ratio between the maximum and the minimum impact parameters. For heavy projectiles of velocity $v = \beta c \approx c$, these scale as γ and γ^{-1}, respectively, which leads to a stopping power essentially proportional to $\log(\gamma^2)$, where $\gamma = (1 - \beta^2)^{-1/2}$. The atoms between the projectile and the interacting target atom screen the field and reduce the ionization probability for large γ values. This "density effect"[1] reduces the logarithmic term by one power of γ. The last γ factor in the logarithm stems from the close collisions. The most probable energy loss is determined by distant collisions only and is particle independent in the gigaelectronvolt region. Hence the most probable energy loss will saturate at a constant "Fermi plateau" for large γ values.

A few years ago, it was pointed out[2] that the strong influence of the polarization of the medium found for energy loss should also be found in measurements of individual ionization cross sections, but in spite of several attempts,[3-7] the effect is claimed to be found in only one experiment.[8] All previous experiments consist of absolute measurements, mostly with electrons, from different accelerators to cover a γ range of 1–10^4. In the present experiment, the large spread

in γ values is obtained because a 1–10-GeV/c secondary beam through the content of protons, pions, and positrons covers a γ value ranging from 1 to 10^5. For 1–10-GeV/c protons, the influence of the density effect is negligible; hence the onset of this effect is easily investigated by simultaneous measurements of x-ray yields for pions and positrons measured relative to the proton yield. The present investigations are dependent upon particle identification, but for 1–10-GeV/c particles this can be done very accurately. Energy-loss measurements have also been made to include the high γ values for comparison.

The experimental apparatus [Fig. 1(a)] was installed in a secondary, nonseparated beam from the CERN 28-GeV proton synchrotron with momenta of 1–10 GeV/c, containing at 5 GeV/c approximately 30% protons (p), 60% pions (π^+), 8% positrons (e^+), and less than 2% kaons (K^+) and muons (μ^+). The beam was defined electronically by scintillators and drift chambers. Vacuum tubes were placed between the first two drift chambers. A 10-mrad bend 15 m upstream from the target removed photons from the incident beam. The particle identification was made with two threshold Cherenkov counters tuned for (e, μ) and (π, K) separation, respectively. Time-of-flight measurements were used to identify protons at 2 GeV/c. Since a correct particle identification was essential in the experiment, a lead-glass array was used as an extra e^+ identification. The x rays were detected with a gas-flow
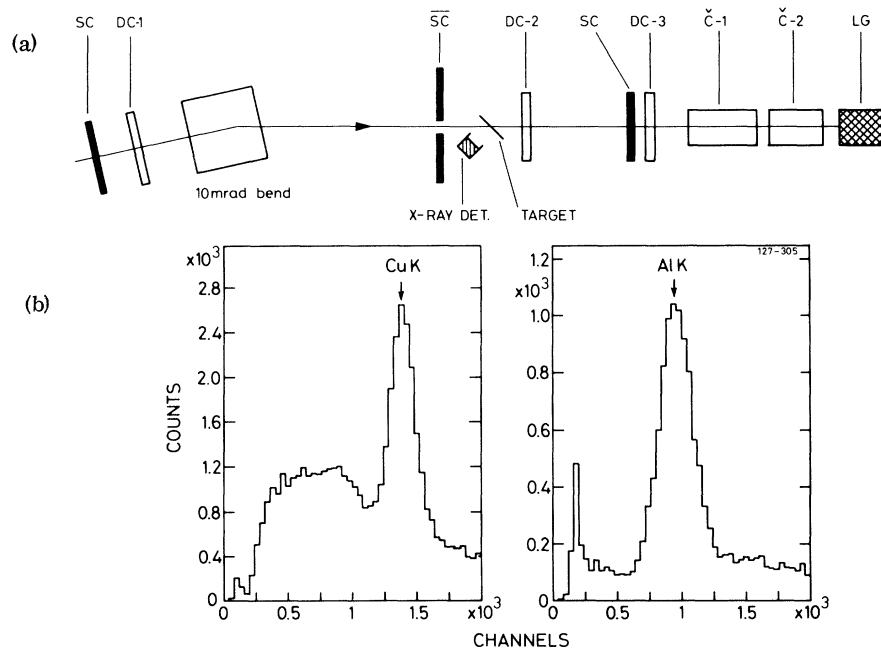
FIG. 1. (a) Schematic drawing of experimental setup. The beam enters from the left. SC designates scintillators; DC, drift chambers; C, Cherenkov counters; and LG, lead-glass array. (b) Measured Cu K and Al K x-ray spectra.

proportional counter, mounted in front of the target normal to the surface. Measured Cu K (~ 8.0 keV) and Al K (~ 1.5 keV) x-ray spectra are shown in Fig. 1(b), with detector resolutions of 15% and 30% full width at half maximum, respectively. The targets were tilted 45° to the beam and had thicknesses of one absorption length of the x-ray line under consideration.

In Fig. 2 measured K-shell excitation cross sections are shown for 5-GeV/c e^+, π^+, and p incident on 25-μm Cu and 10-μm Al targets, all normalized to the proton value. Also shown are the results of previous experiments together with theoretical estimates as obtained in a simple Kolbenstvedt-type approach,[9, 10] where collisions are divided into close and distant ones, the contribution from the latter group being determined in a virtual-photon treatment. The K-shell photoelectric cross section is obtained from tabulated values.[11] For $\gamma \gtrsim 100$, the values corresponding to zero density effect are in agreement with more accurate K-shell cross sections[12] to within 1%, but for $\gamma \sim 5$–10, our values are 5%–10% higher. Spin-flip terms and differences between e^+ and p impact for a given γ are excluded (~ 1%).[13] Bremsstrahlung and δ-ray-induced K-shell excitations are also neglected but may contribute up to 5%. The theoretical curves and the cross sections are normalized to the value calculated for

$\gamma = 5.422$, corresponding to 5-GeV/c protons, here reduced by 7% to compensate for the inaccuracy in the theoretical model at low γ values.[14]

The curve with "full" density effect has been calculated by using the virtual-photon spectrum obtained for a projectile moving in an infinite medium characterized by the frequency-dependent dielectric function $\epsilon(\omega) = 1 - \omega_p^2/\omega^2$, where $\omega_p = (4\pi ne^2/m)^{1/2}$ denotes the plasma frequency for the target material of electron density n. This expression for ϵ is valid to a good accuracy above the K edge.

For a particle penetrating a target, the adjustment of the projectile field from its unscreened vacuum value to the asymptotic screened limit to be reached (deep) inside the target results in the emission of the well-known transition radiation (TR).[1] The TR intensity, $dI^{TR}/d\omega$, all emitted in the forward direction, is essentially equal to the difference between the virtual-photon spectrum in vacuum, $dI^V/d\omega$, and in an infinite medium, $dI^M/d\omega$. As the real TR photons will be absorbed, the total photon intensity at depth z from the target surface is approximately given by

$$\frac{dI^{TOT}}{d\omega} \simeq \frac{dI^M}{d\omega} + \frac{dI^{TR}}{d\omega} \exp\left[\frac{-z}{\lambda_a(\omega)}\right];$$

$$\frac{dI^M}{d\omega} + \frac{dI^{TR}}{d\omega} \simeq \frac{dI^V}{d\omega},$$
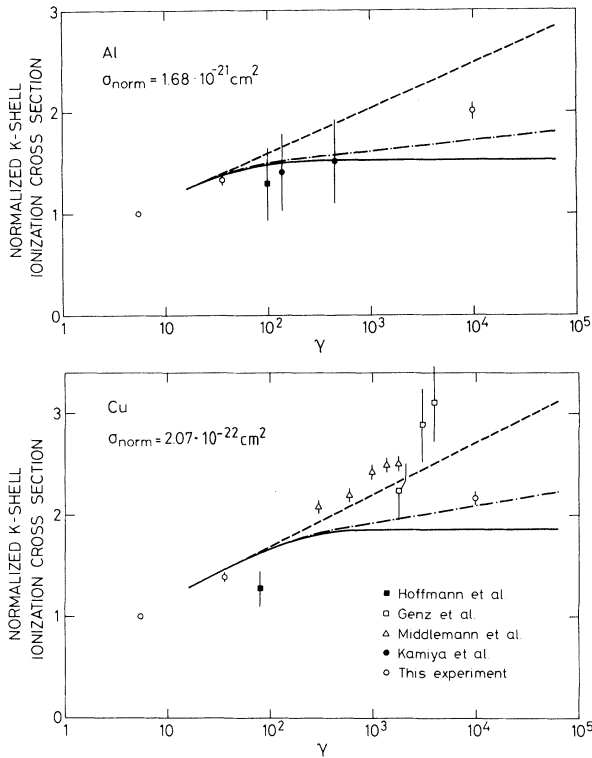
(1)

FIG. 2. Normalized K-shell-excitation cross section in Al and Cu as a function of $\gamma = E/mc^2$. The solid curves are calculated for infinite media by inclusion of the dielectric response, whereas the dashed curves correspond to neglect of density effects. The dot-dashed curves are obtained by use of Eq. (1).

FIG. 3. Measured most probable energy loss, relative to that of 2-GeV/c p, in a 0.3-mm Si detector and a 2.7-mm Ge detector as a function of γ. The solid curve is the Bethe-Bloch formula with the density-effect correction. The dashed curve has been calculated with no density effect on the K-shell excitation.

where λ_a denotes the absorption length. Actually, this relation holds also within the formation zone for TR, although the interpretation of the various photon intensities is less straightforward here (detailed calculations are to be published elsewhere). On top of the K edge, $\lambda_a(K$ edge) is 3.8 μm in Cu and 0.8 μm in Al. Hence Eq. (1) explains the many questions raised till today on the absence of density effects in inner-shell excitations because targets thinner than the respective $\lambda_a(K$ edge) have been used in nearly all previous experiments. A simple understanding of the strong contribution from TR requires clean, homogeneous targets.

On the other hand, targets used in the present investigation have a thickness t, where some density effect should be observed since $t \sim \lambda_a(K\alpha)$ $> \lambda_a(K$ edge). Using the simple model described above and the target geometry and including the self-absorption of the outgoing $K\alpha$ x rays, we find the dot-dashed curves of Fig. 2. At $\gamma = 10^4$, we find the reduction in the ionization yield from
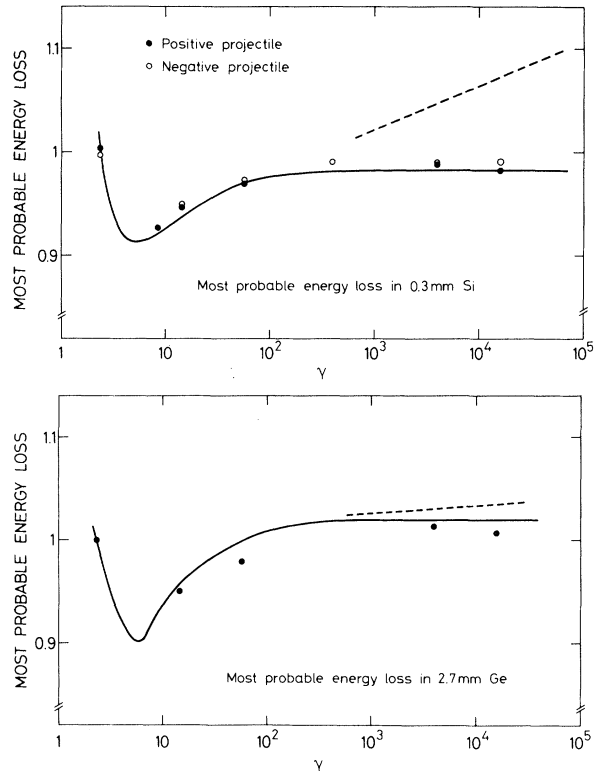
the value obtained without density effects to be 0.76 for Cu and 0.68 for Al. Experimentally we find a reduction of 0.80 for both materials; hence the agreement is good for Cu, whereas there is some discrepancy for Al, which could be due to difference in x-ray background and uncertainty in calculated cross sections.

Lack of density effect in inner-shell excitations has previously been proposed to be caused by a modification of the dielectric function.[7,8,10,15] A reduction of ω_p by more than a factor of 10 would then be required to fit the previous experimental data. However, such a reduction is completely incompatible with experimental transition-radiation spectra such as those presented by, e.g., Cobb et al.[16] Further, the lack of density effect on K-shell excitations should appear in other processes such as energy-loss measurements at high γ values.

Thus the most probable energy loss (MPEL) of 2- and 8-GeV/c p, $\bar{p}$, $\pi^\pm$, and $e^\pm$ has been measured in fully depleted 0.3-mm Si and 2.7-mm Ge

solid-state detectors (the results of a detailed study will be published). The measurements, shown in Fig. 3, are compared to calculated values of the MPEL, using the Bethe-Bloch formula with full density-effect corrections,[17] assuming a Landau distribution of the energy loss. The agreement is within 1%, which is the estimated uncertainty in the measurements. In Fig. 3 are also shown estimates of the MPEL without density effect on K-shell excitations. The experimentally observed flat "Fermi plateau" is clearly incompatible with the lack of a density effect for K-shell electrons, especially for Si. For thinner detectors, however, a moderate rise in MPEL due to TR could be expected. In fact, complete lack of density effect on MPEL has previously been demonstrated experimentally for very thin targets.[18]

A complete understanding of all the competing processes requires much more detailed investigations with x-ray detectors placed in front and at the back, together with variations in target material and thickness.

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