Direct Measurement of He^+ Ions Produced by Compton Scattering between 2.5 and 5.5 keV

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The relative cross sections for Compton scattering have been measured between 2.5 and 5.5 keV. By measuring the number of He^+ ions produced with near zero recoil energies it was possible to identify ions produced by Compton scattering from those produced by photoionization. The results have been placed on an absolute basis by normalization to recent calculations.

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Ionization produced by incoherent scattering from bound electrons in helium can occur at any incident photon energy above 24.6 eV [1–4]. This is allowed because the recoil of the helium ion provides the necessary motion to conserve momentum. No information exists regarding how much energy is transferred from the scattered photon to the atomic system nor how that energy is distributed. Total incoherent scattering cross sections have been calculated and tabulated for all elements by several groups [5–7]. However, these scattering cross sections include both ionization (Compton scattering) and electron excitation (Raman scattering) processes. Recent calculations [8,9] of Compton scattering have included the contributions of single and double ionization.

At photon energies in the high kilovolt range bound electrons are expected to behave as free electrons (as observed originally by Compton [10]) from which the photons are elastically scattering giving up some energy to the electrons in accordance with the laws of conservation of energy and momentum. Hence in this high energy region we would expect the residual ions to have negligible recoil energies. This is in sharp contrast to the photoabsorption process where the photon energy is completely lost and a photoelectron is ejected with a similar energy less the atomic binding energy, thus creating an ion with appreciable recoil energy. For example, absorption of a 10 keV photon by He would produce an ionic recoil energy of about 1.4 eV. Thus, measurements of ionic recoil energies should allow us to distinguish between photoabsorption processes and ionization produced by incoherent scattering. In keeping with the nomenclature used in Refs. [3] and [4] we refer to this latter process as Compton scattering.

Although Compton scattering has been investigated on and off since 1923, no studies have been made on any atomic gas at energies where the effect of scattering from bound electrons may be significant. In this Letter we present measurements of the Compton scattering cross sections for helium between 2.5 and 5.5 keV by direct measurements of low energy ions (0–50 meV). Recoil energies of ions produced by photoabsorption in this energy range are calculated to be 0.34 to 0.75 eV. The effects of coherent and incoherent scattering become noticeable for photon energies greater than 2 keV [11,12]. The presence of Compton ions in measurements of the He^{2+}/He^+ ratio also becomes important at energies greater than 2 keV [13,14]. Thus, this is an interesting region in which to study Compton scattering.

We have chosen a method for studying the relative Compton ionization cross section (i.e., ions produced per incident photon) which exploits a high collection efficiency for "zero" energy ions (0 to 50 meV) compared with energetic ions. If there are Compton ions with more energetic recoil energies present, they will not be detected by the present equipment; therefore our measurements reflect the cross sections for producing zero energy recoil ions. The above ionic recoil energies will, of course, have the room temperature Maxwell energy distribution superimposed.

Our experimental arrangement consisted of an ion chamber, a hemispherical energy analyzer, and a mass spectrometer. The ion chamber was designed for maximum extraction efficiency of zero energy ions (0–50 meV). The energy scale of the analyzer was calibrated to determine the peak position for room temperature He^+ ions. After extraction, the ions were accelerated to 5 eV to match the pass energy of the energy analyzer. This gave an energy resolution of 75 meV. On leaving the analyzer the ions were accelerated to 90 eV before entering the mass spectrometer. The experiments were performed on the LANL beam line XBA at the National Synchrotron Light Source at Brookhaven National Laboratory. A Si(111) double crystal monochromator provided radiation between 2.1 and 5.5 keV. Helium, introduced into the ion chamber, was free to escape through two 5 mm diameter holes provided for the incident radiation to pass through. The estimated pressure inside the ion chamber ranged from about 10^{-4} to 10^{-3} torr. The intensity of incident radiation was monitored with a calibrated aluminum photodiode. A 0.5 μm Ni filter was used to eliminate the specularly reflected radiation and any scattered radiation from the monochromator for energies up to several hundred eV. Measurements of He^+ ions were made between 2.1 and 5.5 keV. Zero energy

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peaks were observed at each energy. Because the ion chamber strongly discriminated against ions with energies greater than 50 meV it was not feasible to measure the higher recoil energies of the photoions. However, when the gas pressure in the ion chamber was high ($\sim 10^{-3}$ torr) increasing numbers of zero energy ions were observed as the photon energy was decreased towards 2.1 keV. Presumably, the ions were produced by thermalization or charge transfer between the energetic photoions and the neutral helium atoms. These extra ions disappeared as the pressure was reduced. The fact that the low pressure data produced zero energy ions is conclusive evidence that the ions were produced by Compton scattering. Data were taken at both high and low pressure. The relative number of ions produced per incident photon at the higher pressure are shown in Fig. 1 as a function of the incident photon energy. The error bars indicate an uncertainty of $\pm 10\%$. The solid line is drawn to give a best fit to the data.

At a sufficiently low pressure, so that no thermalization took place, relative cross sections were measured between 3.5 and 5.5 keV. The statistical errors were $\pm 37\%$. These results are shown in Fig. 2 (open circles). The data have been normalized by eye with the calculated cross sections of Hino, Bergstrom, and Macek [8] (open squares). The dashed curve represents the total incoherent cross sections calculated by Hubbell *et al.* [5]. The data represented by the solid curve and closed circles were obtained by analysis of the high pressure data as follows. Because the data are a mixture of Compton ions and thermalized photoions we can equate the observed cross section (σ_{obs}) to the total photoionization cross section (σ_p) and Compton ionization cross section (σ_c^+) as follows:

$$\sigma_{obs} = f_p\sigma_p + f_c\sigma_c^+ , \qquad (1)$$

where f_p and f_c denote the fraction of σ_p and σ_c^+, respectively, that contributes to the total ion signal. σ_{obs} is measured (in relative units), σ_p is known [11], and σ_c^+ has been calculated by Hino, Bergstrom, and Macek [8]. Using their theoretical values for σ_c^+ at 3 and 3.5 keV we can determine the average values for f_p and f_c for a given pressure. The resulting values for the product $f_p\sigma_p$ are shown in Fig. 1 by the dashed line. The difference between the solid and dashed lines gives the value of $f_c\sigma_c^+$; hence σ_c^+ is determined. We have taken the solid line in Fig. 1 to represent our smoothed experimental data and have determined σ_c^+ from 2.5 to 5.5 keV by use of Eq. (1). This results in a curve that is effectively normalized to theory at 3 and 3.5 keV. These results are shown in Fig. 2 by the solid line curve. Normalization at any two energies between 2.5 and 4.5 keV gives similar results. However, above 4.5 keV a small error in the observed signal magnifies the uncertainty in data at 3 keV and below. Individual data points at 2.5, 3, 4, 5, and 5.5 keV, obtained by evaluating the measured value of σ_{obs} in Eq. (1) and solving for σ_c^+ are shown in Fig. 2 by the closed circles. The error bars represent an overall uncertainty of $\pm 26\%$. We cannot extract a meaningful value for σ_c^+ from the data point at 2.1 keV because it is produced primarily by photoionization. The energy dependence of the experimental curve is in good agreement with that of the calculated data. This agreement suggests that Compton ions produced between 2.5 and 5.5 keV all have very low recoil energies. However, without measuring the full recoil energy spectrum of the Compton ions we cannot draw any definite conclusions about the recoil energy distribution.

In summary, we have measured the relative cross section for the production of "zero" energy ions by Compton scattering from helium between 2.5 and 5.5 keV. Fur-

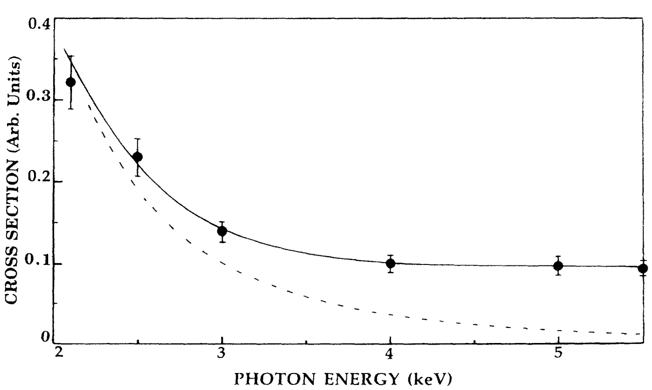

FIG. 1. The observed relative ionization cross section (σ_{obs}) measured as a function of the incident photon energy. The solid line represents a best fit to the experimental data. The dashed curve represents the fraction ($f_p\sigma_p$) of σ_{obs} that is produced by thermalized photoions. The difference between the dashed and solid lines gives the relative Compton ionization cross section.

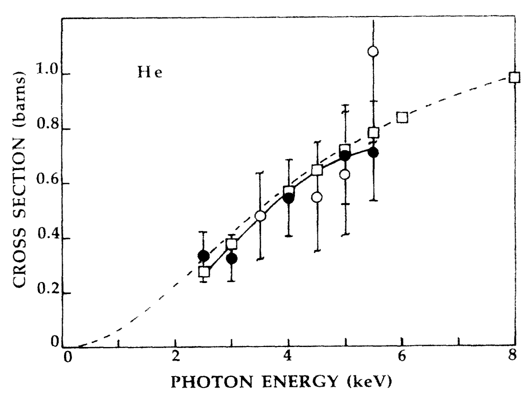

FIG. 2. Total Compton scattering cross section as a function of the incident photon energy. Closed circles and solid line represent the present data obtained at "high" pressures. Open circles represent data at "low" pressures. Open squares represent the calculated Compton cross section (Ref. [8]). Dashed curve represents the calculated total incoherent scattering cross sections (Ref. [5]).

ther, it has been shown that Compton ions can be distinguished from those produced by photoionization by measuring the ionic recoil kinetic energies in the above energy region.

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