Double Ionization of He by Fast Protons at Large Energy Transfer

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The ratio $R(\Delta E)$ of double to single ionization of He by fast proton impact has been measured as a function of energy transfer (ΔE). While $R(\Delta E)$ is observed to be nearly independent of proton energy (1–6 MeV) within experimental error, it decreases with increasing energy transfer, from 2% at $\Delta E = 1$ keV to below 1% at $\Delta E = 10$ keV. Further comparisons of these ratios with those obtained from photoionzation and Compton scattering are made. [S0031-9007(96)00315-8]

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In fast collisions, double ionization of He requires interaction of its two electrons in addition to a quick interaction with the projectile. Because mechanisms for the interaction with the projectile are relatively simple for these fast collisions, observations of double ionization provide an opportunity to study mechanisms for the dynamics of electron correlation in an atomic system [1,2]. A simple approach is to study the ratio R of double-to single-ionization cross section. When the collision is fast enough, R is observed to approach a constant value, independent of projectile energy. For charged particle and antiparticle impacts, the asymptotic value is 0.26% [3–7], in good agreement with theories [8,9]. It is 1.7% for photoionization [10–12], also agreeing with various theoretical predictions [13–18]. By contrast, the high energy limit for Compton scattering is elusive. It is still under investigation experimentally [10,19], while theoretical predictions remain controversial [15,20–23].

Of particular interest is the interconnection between R obtained by charged particles and by photons [1,2,24,25]. They are in principle related to each other because both charged particles and photons interact with He in the same way: via electromagnetic fields. The seemingly big difference between the asymptotic ratios due to charged particle scattering and photoionization can be explained by the fact that photons impart all their energy to the ionized electrons, while the ionization by charged particles is dominated by soft collisions, for which outgoing "primary" electrons are slow [25]. Hence, the two electrons may interact quite differently in these two cases. On the other hand, one would expect a much smaller, if any, difference if the production of fast primary electrons in charged particle scattering is isolated. This has indeed been observed. A substantially higher ratio near 2%, very close to that for photoionization, is observed in fast proton-He collisions, where the fast primary electrons were selected either kinematically [26] or directly [27,28].

On the theoretical side, the subject has drawn renewed interest [2,29–31] very recently, partially driven by the flurry of new experiments at synchrotron light sources [10–12,19], and theoretical calculations for photoionization and Compton scattering [13–18,20–23]. Although a higher ratio close to that for photoionization was observed for charged particles when fast electrons were isolated [26–28], the difference between charged particle scattering and photoionization still remains. While a charged particle probes electrons in all its initial momentum space, a photon only interacts with electrons with high initial momentum in photoionization because the photon is annihilated and it carries very little momentum. It has been realized lately that ionization by charged particles is perhaps more closely related to that by Compton scattering, in which a photon transfers only part of its energy to electron(s). For collisions where first order perturbation approximation is valid, the ratio $R(\Delta E)$ as a function of energy transfer (ΔE) is predicted to be the same for both Compton scattering and charged particles at large ΔE [29]. At smaller energy transfer ("small" in this work still requires the ejected electron to be fast), both Compton scattering and charged particle scattering are related to photoionization in first order [30,31].

In this Letter, we report the first direct measurement of $R(\Delta E)$ in fast proton-He collision. Here the energy transfer ΔE was measured directly and completely by measuring the energy loss of protons after the collision, whereas previously ΔE was either calculated by assuming binary kinematics between protons and electrons [26] or measured at one particular electron emission angle [27,28]. The new method has the advantage of much higher efficiency, equivalent to measuring electrons emitted into 4π solid angle, and thus avoids the possible complication due to angular correlation [28]. Indeed, it provides us the opportunity to measure $R(\Delta E)$ at much larger ΔE, where a trend of decreasing $R(\Delta E)$ with increasing ΔE has been observed for the first time. $R(\Delta E)$ drops from 2% below $\Delta E = 1$ keV to less than 1% at $\Delta E = 10$ keV, close to the asymptotic value for Compton scattering (0.8%) predicted by Andersson and Burgdörfer [15] and Surić *et al.* [21]. The trend of decreasing $R(\Delta E)$ with increasing ΔE for proton impact also resembles the trend predicted for Compton scattering [29].

The experiment was carried out in the EN Tandem facility at ORNL. The experimental apparatus is shown in Fig. 1. A proton beam of energy 2–6 MeV from the tandem Van de Graaff accelerator was energy defined by the analyzing and switching magnets coupled with

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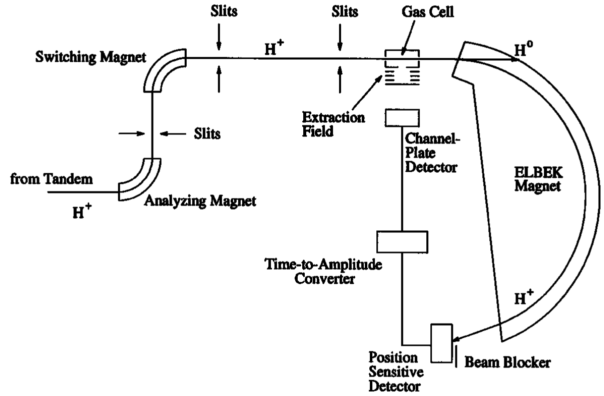

FIG. 1. Schematic diagram of the apparatus.

two sets of slits right after the magnets. The angular divergence of the beam was defined by a third set of slits in front of the gas cell. After passing through the gas cell containing He at a pressure between 0.6 and 0.8 mTorr, the scattering protons were energy analyzed by the Elbek magnetic spectrograph [32,33] and detected by a two-dimensional position sensitive channel-plate detector (PSD) located in its focal plane. Except for the measurements of total cross sections, the main beam (energy unchanged) was stopped by a beam block so that only protons which lost energy above a chosen amount were detected. The He ions created in the cell were extracted perpendicular to the beam by an electric field of 140 V/cm over 1.4 cm. After drifting another 6.2 cm, they were detected by a channel-plate detector. Double ionization was separated from single ionization by measuring the flight time between the detection of the protons and the He ions. The ratio between the production of He^{2+} and He^{+} was found to be independent of gas pressure within experimental error ($\sim$18%). Moreover, the total cross section ratio R was found to be $(0.29 \pm 0.03)\%$ for 2 MeV protons, in agreement with the previous measurements of $(0.28 \pm 0.03)\%$ [6] and $(0.276 \pm 0.006)\%$ [7].

A key part of the experiment is the energy calibration of the position on the PSD. For proton beams, a direct calibration such as a "voltage labeling" technique in charge exchange processes [33] is impossible. Instead, the following indirect method was adopted. For a beam of given momentum P, a momentum change δP will cause its peak to move a distance δx along the focal line [32]:

$$\delta x = D \frac{\delta P}{P}, \tag{1}$$

where the dispersion D is a constant. On the other hand, the change of the magnetic field B will also shift the peak position of a beam with fixed momentum. It can be easily shown [32] that

$$\delta x = -D \frac{\delta B}{B}. \tag{2}$$

In the experiment, the dispersion D was first determined by measuring the change of the peak position (δx) against the change of the Elbek magnetic field (δB) according to Eq. (2). Afterwards, the energy transfer ΔE, which is the same as the energy loss of protons, was measured,

$$\Delta E/E = 2\Delta P/P = 2\Delta x/D. \tag{3}$$

The beam energy E was determined by the accelerator. The energy resolution in this experiment was mainly limited by the size of the beam, which was about 0.4 mm on the PSD, equivalent to a relative energy resolution ($\delta E/E$) of 4×10^{-4}.

Figure 2 shows energy-loss spectra for single ionization of He. The artificial cutoff at low energy transfer is due to the blocking of the main beam. The main feature of the spectra is the dropoff at some critical energy transfer. This can be understood in terms of a binary collision between a proton and one of the target electrons; there is a maximum energy that a proton can transfer to a free electron. Such limits are marked in Fig. 2 where they are seen to coincide with the observed experimental dropoffs. The sharp drop predicted by a free electron is partially washed

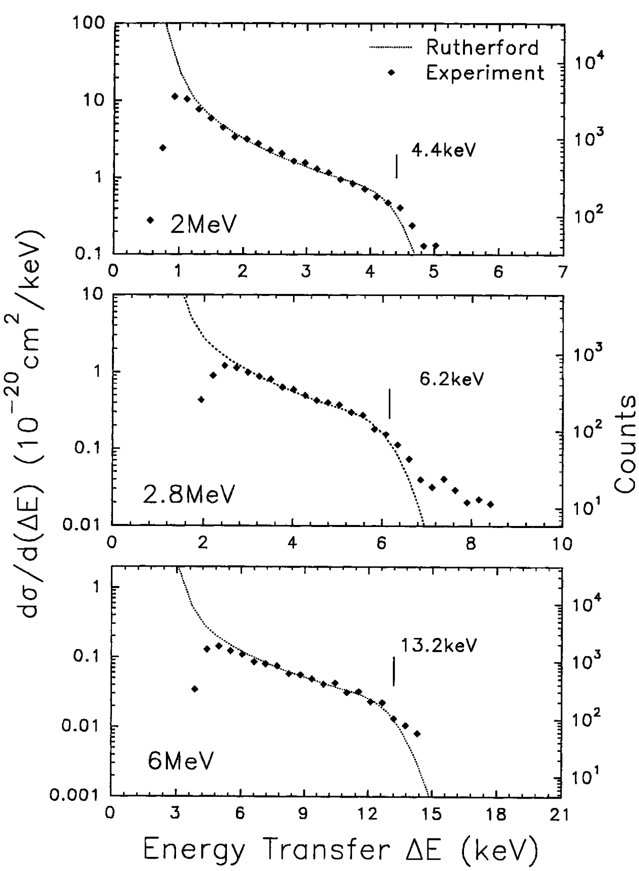

FIG. 2. Energy loss spectra for single ionization of He by protons. The cutoffs at low energy transfer are artificial due to the blocked main beam. The curves are Rutherford calculations for a proton scattered from an electron multiplied by two. The vertical marks indicate the maximum energy a proton can transfer to a free electron at rest.

out by the initial electron momentum distribution in the atom and the experimental resolution. Calculations based on Rutherford scattering of a proton from a free electron [34] are compared with the measurements in Fig. 2. Since the experimental resolution (0.8 keV for 2 MeV protons) is much larger than the spread of He Compton profile (FWHM $= 0.04$ keV), only the experimental resolution has been folded into the calculations shown. The agreement between the shape predicted by this simple model and that measured in the experiment is remarkable, suggesting that single ionization at such large energy transfer is predominantly attributed to the scattering of protons from quasifree target electrons. This quasifree electron process in single ionization has previously been observed in large angle ($\geq$0.2 mrad) scattering of protons [26].

The measured $R(\Delta E)$ are shown in Fig. 3, where they are compared with the proton data measured by different methods [26–28] and calculations for photoionization [16] and Compton scattering [29]. One critical question for the present experiment is the possible contributions to double ionization from independent interactions of the proton with both He electrons (second order effect) [1,2,7,24]. The data in Fig. 3(a) show a very weak projectile energy dependence of $R(\Delta E)$. At ΔE around 0.5 keV, $R(\Delta E)$ obtained from 1 and 3 MeV protons [26,27] are almost the same as those obtained from 40 MeV protons [28], for which there should be no question about second order contributions. The lack of collision energy dependence in $R(\Delta E)$ resembles the observation for the total cross section ratio R. R was found to decrease very slowly from $(0.276 \pm 0.006)\%$ for 2 MeV protons to $(0.249 \pm 0.10)\%$ for 10 MeV protons [7], whereas the asymptotic value is expected to be 0.26% [8]. Such energy (in)dependence of R and $R(\Delta E)$ is certainly not a proof that the second order effect is excluded in the present experiment. By contrast, the significantly higher R for antiprotons [4,7] than for protons demonstrates the importance of the second order effect. The weak energy dependence of R for protons is caused by the near complete cancellation of the contributions of the second order term and the interference term between the first and second order processes [7], a coincidence which occurs for particles with charge of 1. As the data suggest, such cancellation seems also to occur in $R(\Delta E)$, a differentiation of R. The multiple interaction of protons with He is present in our experiment, but the net contributions due to this process seem very small.

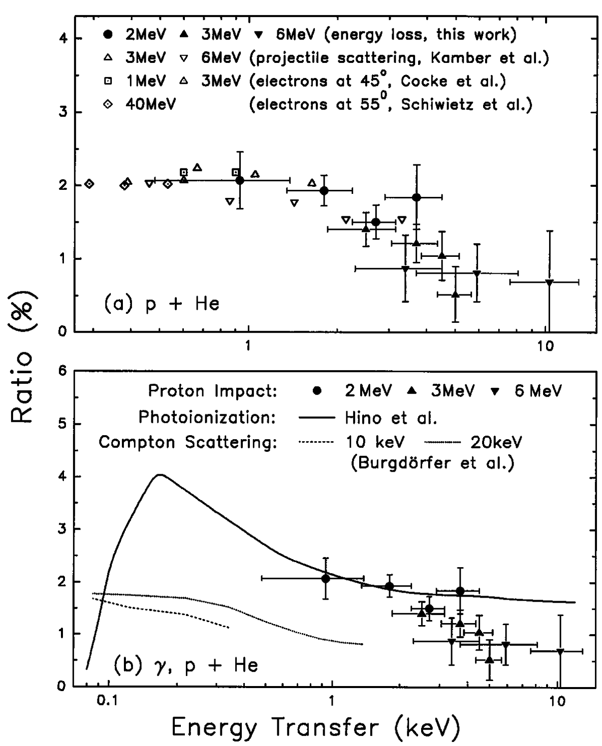

FIG. 3. Ratio of double to single ionization of He as a function of energy transfer from projectiles to He. Other experimental results for proton impact are from Kamber *et al.* [26], Cocke *et al.* [27], and Schiwietz *et al.* [28]. Theoretical curves are from calculations for photoionization by Hino, Bergstorm, and Macek [20] (solid line), and for Compton scattering by Burgdörfer *et al.* [29] (dashed lines).

The key finding of this experiment is that $R(\Delta E)$ decreases with increasing ΔE. At low energy transfer ($\Delta E < 2$ keV), $R(\Delta E)$ lies near 2%, in good agreement with the predictions for photoionization [14–18] (since photons are annihilated in photoionization, ΔE is simply the incident photon energy). The same value of $R(\Delta E)$ for charged particle impact and photoionization is expected within the validity of the Bethe-Born approximation [25,30,31]. However, with increasing ΔE, $R(\Delta E)$ starts deviating downwards from that for photoionization at the energy transfer region where previous measurements end. At $\Delta E = 10$ keV, $R(\Delta E)$ drops below 1% and approaches the asymptotic value for Compton scattering predicted by Andersson and Burgdörfer (0.83%, [15,23]) and Surić *et al.* (0.80%, [21]), but significantly lower than predictions by Hino, Bergstorm, and Macek [20] and Amusia and Mikhailov [22] (both quote 1.7%, i.e., about the same as photoionization limit). If $R(\Delta E)$ obtained from charged particle scattering is indeed the same as that obtained from Compton scattering as theories predict [29,31], the present data indicate that the asymptotic value of R for Compton scattering is more likely to be 0.8% rather than 1.7% [23], because the ratio R for Compton scattering, which is the integral of $R(\Delta E)$ over all ΔE, is dominated by contributions from large ΔE [29]. A direct comparison of our measurements with $R(\Delta E)$ for Compton scattering is not readily available. Instead, $R(\Delta E)$ for Compton scattering of 10 and 20 keV photons from He [29] are included in Fig. 3(b). A very similar trend can be seen for both Compton scattering and charged particle scattering. Comparing the 10 and 20 keV Compton scattering results indicates that better agreement between Compton scattering and charged particle scattering can be expected at higher photon energies. For an energy transfer of 10 keV, one would require photons of energy above 50 keV.

In conclusion, we have measured the ratio of double to single ionization of He by fast protons as a function of energy transfer from the proton to the target atom. While $R(\Delta E)$ seems nearly independent of proton energy, it decreases with increasing energy transfer. $R(\Delta E)$ overlaps with that for photoionization at relatively small energy transfer ($\sim$0.1–2 keV), but deviates towards a value below 1% at energy transfer near 10 keV. This trend for proton impact resembles the predictions for Compton scattering [29]. The measurement strongly suggests that the asymptotic limit of R for Compton scattering is more likely to be 0.8% [15,21,23] instead of 1.7% [20,22], a value about the same as that for photoionization. The implication is that in the processes where a fast primary electron is created $R(\Delta E)$ from charged particle impact becomes comparable to that from Compton scattering or photoionization. The specific value of the ratio, however, does depend on how that fast primary electron is removed, in other words, on where in its initial momentum space this electron comes from. This further suggests that in different regions of the initial two-electron state, the correlation of the two electrons is different, causing different contributions to double ionization from charged particle impact, Compton scattering, or photoionization.

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