# Experimental Observation of the Thomas Peak in High-Velocity Electron Capture by Protons from He

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Experimental angular distributions are reported for electron capture by protons of 2.82, 5.42, and 7.40 MeV from He. A clear peak in $d\sigma/d\theta$ appears near the Thomas angle of 0.47 mrad for the higher two bombarding energies, supporting the widely held belief that the double-scattering mechanism plays an important role for high-velocity electron capture.

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In 1927 Thomas[1] gave a classical treatment of the capture by a fast point projectile of a bound electron whose orbital velocity ($v_e$) is much less than the velocity of the projectile ($v_p$). The process he described involved a double scattering whereby the nearly free electron is first scattered off the projectile at a laboratory angle of 60°, for which it attains a velocity equal to that of the projectile, and then elastically off the target nucleus to redirect this velocity vector in the direction of the projectile. It is now widely understood that any quantum treatment of high-velocity capture must take this process into account.[2] In a perturbation expansion, it corresponds to a second-order Born process[3,4] in which the projectile-electron and target-electron potentials each act once, and indeed the second-order Born term dominates over the first-order Born in the limit of high $v_p$.[5] Several high-velocity theoretical treatments[6-15] have now been given which include second- and higher-order terms and which have been quite successful in accounting for experimental total cross sections. By contrast, the first-order Born results are well known to be too large by a factor typically near 3.

A differential cross-section measurement provides a much cleaner way to isolate the Thomas scattering mechanism than do the total cross sections. In the classical two-collision treatment, the projectile is scattered to the Thomas angle, $\theta=\sqrt{3}m/2M$, (where $m$ and $M$ are electron and projectile masses, respectively). In the quantum treatment, the corresponding process is revealed by a peak (or shoulder) in the differential cross section at this angle.[2,3,6,12,16-18] This feature becomes increasingly marked as $v_p$ is increased.[6,16] The frequently proposed[17,19] experimental detection of such a peak would provide evidence that the fundamental physical process has been correctly identified. Further, as recently discussed by Briggs, Greenland, and Kocbach,[19] the exact shape of the angular distribution inside the Thomas peak is quite sensitive to the relative contributions of first- and higher-Born terms in a perturbation expansion, and thus experimental measurements of differential cross sections in the high-velocity region provide much more sensitive tests of the theoretical treatments than do total–cross-section measurements. This paper reports experimental detection of a peak in the angular distribution for high-velocity electron capture by protons from He. This peak occurs near 0.47 mrad and is interpreted as the first experimental detection of the Thomas peak in electron capture.

In the experiment we measured the differential cross section for electron capture by protons from He at 2.82, 5.42, and 7.40 MeV, corresponding to $v_p/v_e$ of 7.95, 10.8, and 12.9, respectively. Here $v_e$ is taken to be $(2mU_K)^{1/2}$, where $U_K$ is the ionization energy for He. While most published theoretical cross sections are for an atomic hydrogen target, it is an important experimental consideration to optimize the target thickness, since the absolute differential cross sections in the asymptotic region are quite small. At the required pressures for a hydrogen target, substantial molecular dissociation becomes quite difficult to obtain. Plane-wave second-Born (B2) calculations by Simony, McGuire, and Eichler[16] for He show structure in the vicinity of the Thomas angle at energies as low as 5 MeV for the case of the He target, and comparisons with strong-potential second-Born (SPB) and impulse-approximation treatments of the $p$-H system suggest that the peak should be even more pronounced than the B2 calculations indicate.[19]

Two major considerations shape the design of the experimental arrangement. First, because the Thomas angle is so small ($\theta_T=0.47$ mrad for proton projectiles), tight beam collimation is necessary. Second, because the differential cross section is quite small ($d\sigma/d\Omega \simeq 0.06 a_0^2$/sr-atom at 0° and 7.4 MeV), a high fraction of all scattering events must be recorded. The arrangement we used is shown in Fig. 1. A proton beam from the Kansas State University's tandem Van de Graaff accelerator was collimated by passage through apertures separated by 5 m, whose dimensions were 0.3 mm high by 0.10 mm wide (set 1) and 0.2 mm high by 0.05 mm wide (set 2). The beam was charge purified by passing it through a 3° bending magnet 1 m before entering the 27-cm-long He gas cell. The entrance and exit apertures of the cell were 1.0 and 3.0 mm in diameter, much larger than the beam. After the gas cell the proton beam was deflected into a Faraday cup while the hydrogen atoms formed from capture proceeded onto the face of an ion-implanted position-sensitive detector (nominal resolution full width at half maximum ≈ 0.1 mm), located 5.7 m downstream from the target region. This detector was covered by a mask shaped like a bow tie, with a full half-tie angle of 45°, positioned such that the angular distribution was centered on the mask center to within 0.1 mm. Although the detector signal is strictly one-dimensional only, the $x$ distance of an event from the mask center differs from the radial distance from the center by a maximum of 8%, and an average of only 3%, much less than the overall experimental resolution. For a precisely aligned mask, the position spectrum reflects the quantity $d\sigma/d\theta$, where $\theta$ is the laboratory scattering angle. Helium pressures as high as 177 mTorr (at 7.4 MeV) were used, the limiting factors being loss of angular resolution due to multiple scattering in the target and collisional loss of hydrogen atoms in the cell following capture. Absolute total cross sections were obtained from the measured beam current and target pressures with the hydrogen beam hitting an open part of the mask, and were found to be in agreement within 20% with the previously measured values.[20,21] The absolute scales for the results shown in this work were assigned by normalizing the integrated differential cross sections to values of $1.85\times10^{-23}$, $5.25\times10^{-25}$, and $9.23\times10^{-26}$ cm$^2$ for energies of 2.82, 5.42, and 7.4 MeV, respectively. These values lie on a smooth curve through all available total-cross-section data.

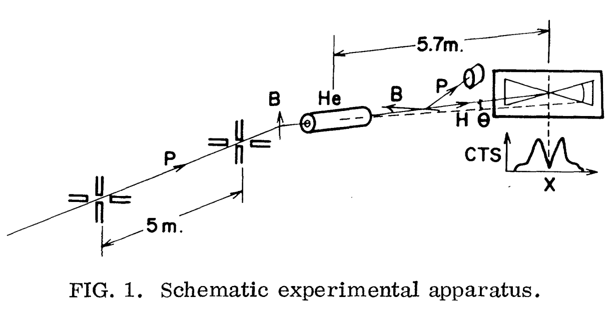


FIG. 1. Schematic experimental apparatus.

Typical spectra from the position sensitive-detector are shown in Fig. 2 for 7.4-MeV protons on targets of both He and Ne. The latter target was used as a control, since no Thomas peak would be expected for this case. Capture for Ne at this energy proceeds mainly from the $K$ shell[22] and is made possible by the large momentum components available in the initial-state wave function. Thus for Ne, $v_p/v_e$ is only 2.1 and the Thomas peak is lost in the large central maximum of the angular distribution. For the He case there are clear peaks on either side of the beam center located at approximately the Thomas angle.

After subtraction of a small background (10%–20%) obtained by diverting the gas flow from the target cell to the vacuum system directly the position spectra were converted to angular distributions by dividing by the solid angle for each position increment and normalizing to the total cross sections given above. This procedure removes the slight asymmetry seen in Fig. 2 which is caused by a small difference between the positions of the centers of the beam and the collimating mask.

The angular distributions on either side of the

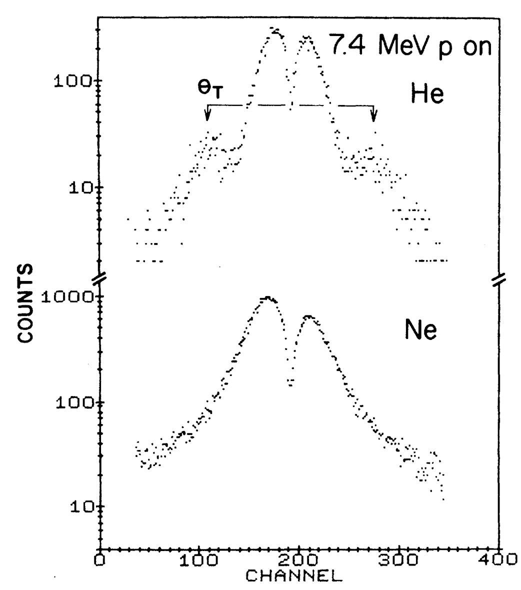


FIG. 2. Typical spectra from the position-sensitive detector.

beam could then be superimposed on a single plot. In order to emphasize the peak, and better to show the relative sizes of contributions from central maxima and Thomas peak to the total cross section, we have chosen to present our results in terms of $d\sigma/d\theta$ vs $\theta$ instead of $d\sigma/d\Omega$ vs $\theta$.

Typical angular distributions are shown in Fig. 3 for three bombarding energies. The Thomas peak is seen to become rapidly weaker as the bombarding energy is lowered, disappearing altogether for the 2.82-MeV case. Even at this lower energy, however, there remains a qualitative change in the slope of the angular distribution near 0.3 mrad. It has been recently pointed out by Briggs, Greenland, and Kocbach[19] that an interference minimum between first- and higher-order Born terms appears in the impulse approximation and SPB formulations at an angle of $m/2M$ (=0.27 mrad for this case). The slope change seen in the data may be due to this interference. Indeed, such a slope change is present in previously published angular distributions at much lower energies[23, 24] where there could be no hope of seeing the Thomas peak itself. Thus it seems probable that the importance of the higher-order Born terms is displayed in angular distributions even at lower energies even though it has not been specifically so identified previously.

In Fig. 3 we also show the results of folding our experimental resolution function together with two theoretical calculations. This resolution function

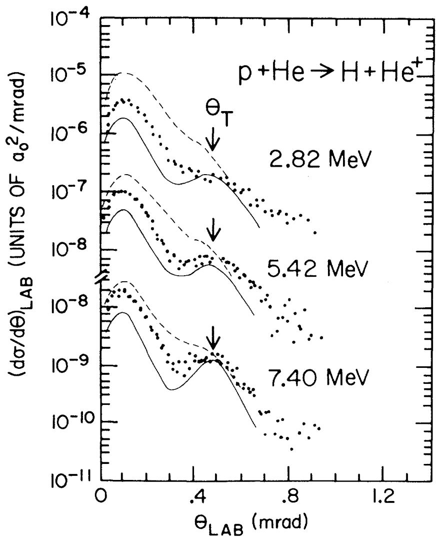


FIG. 3. Plots of $d\sigma/d\theta$ vs $\theta$. The dots are the present experimental data. The theoretical cuves are B2 (dashed) (Refs. 16 and 25) and SPB (peaking, solid line) (Refs. 7 and 25).

was determined without changing the target pressure by taking a position spectrum of the direct beam hitting an open part of the mask and could be well represented by a Gaussian of full width at half maximum near 0.058 mrad superimposed on a second Gaussian of approximately one third the strength and full width at half maximum of 0.21 mrad. The latter was apparently due mainly to multiple scattering. The two theoretical distributions are the plane-wave second Born[16, 25] and the SPB[25] with the peaking approximation described by Macek and Alston.[7] Both calculations appear to fail worst in the region of the central maximum, where the major contributions to the total cross section lie. The B2 overestimates the total cross section by a factor of 1.5 to 3, while the SPB is too low by about a factor of 2. In the region of the Thomas peak, the SPB does quite well in $d\sigma/d\theta$, while the B2 appears to retain too much of the central maximum at these large angles. The exaggerated minimum in the SPB near 0.3 mrad is emphasized by the weakness of the central maximum which may be due to the inadequacy of the peaking approximation. For the angles outside 0.5 mrad the experimental curves appear to have somewhat less slope than do the theoretical curves. This could be due to a neglect of scattering due to the internuclear Coulomb potential in the calculation, since it is in just this region that such effects should begin to be significant. The 2.82-MeV distribution is very close to Rutherford scattering in shape outside 0.3 mrad.

In summary, we report the experimental observation of a peak in the differential cross section for high-energy electron capture by protons from He. This peak occurs at a laboratory scattering angle near $\sqrt{3}\,m/2M$ and is interpreted as due to the double-scattering mechanism of Thomas. This experimental result strongly supports the widely held belief in the importance of the double-scattering mechanism at high velocity. While the experimental angular distributions are qualitatively similar to those from second Born and strong-potential Born (peaking) calculations, the former overemphasizes the central maximum in the distributions while the latter underemphasizes it. It appears that a quantitative understanding of the present data requires more theoretical work to be done on high-velocity angular distributions.

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