Ramsauer-Townsend Effect in the Electron Loss from H^0 Colliding with Heavy Atoms

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The emission pattern of loosely bound projectile electrons is strongly dependent on the target species. For 0.5 MeV hydrogen colliding with krypton we observe large variations in the intensity of these electrons as a function of emission angle. There are also large changes in the energy and width of the electron loss peak associated with these intensity variations. These features are closely related to the Ramsauer-Townsend scattering of free electrons and can be interpreted within the electron impact approximation, a model which successfully combines free electron scattering by the heavy target with the Compton profile of the initially bound projectile electron.

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One of the fundamental processes occurring in heavy ion collisions is the ejection of electrons. A study of their energy and angular distribution provides a unique insight into the collision dynamics and into the atomic structure of the collision partners [1]. With the availability of recent more accurate measurements one has a sensitive test of traditional theoretical models and those being newly developed. An essential feature in the spectrum arising from projectiles which carry electrons into the collision is in "the electron loss peak" which was independently discovered by Burch, Wieman, and Ingalls [2] and Wilson and Toburen [3] and identified to originate from these projectile electrons. Since the peak is located at an energy which approximately corresponds to the energy of the outermost projectile electron in the target rest frame, one of the earliest interpretations was based on the idea that electron loss might be treated as an elastic collision between the projectile electron and the target atom. Free electron-atom scattering (as reviewed by, e.g., Bransden and McDowell [4]) is a field which has been thoroughly investigated in order to get detailed information about the electronic properties of the target. As early as the 1920s, Ramsauer [5] and Townsend and Bailey [6] discovered pronounced structures in the energy dependence of the elastic scattering cross section from heavy rare gas atoms. Later investigations [7,8] have revealed that these intensity variations arise from deep minima in the angular dependent differential cross sections. These structures, which can be reproduced with the help of close-coupling calculations [9,10], have been interpreted in terms of interference effects between the different partial waves contributing to the scattering amplitude. The absence of structures for helium targets and the increase of the number of minima with increasingly heavier rare gases (at fixed impact energy) could then readily be explained by the number of partial waves required: only a few for He, but some tens for the heaviest gases.

Menendez and Duncan [11] were the first to discover structures in the angular dependent singly differential cross section in the case of clothed ion impact. Somewhat surprisingly, subsequent measurements of doubly differential electron loss cross sections from hydrogen or helium impact on all rare gases up to Kr [12–14] did not reveal any Ramsauer-Townsend effects on the electron loss peak itself. Both peak position and peak width were found to depend smoothly on the ejection angle within the experimental errors, thereby throwing some doubt on any theory derived from free electron scattering. We now believe these experiments were hampered by two circumstances. First, the use of mostly He^+ projectiles with their rather tightly bound electron for electron loss peak investigations [13] produced a rather high background of target electrons relative to loss electrons. This made it difficult to extract the precise peak shape for backward emission angles. Second, the backward hemisphere was only explored with He, Ne, and Ar targets [13–15] and at such high collision velocities that Ramsauer-Townsend effects are either absent (He, Ne) or rather weak (Ar). The heaviest target used so far for electron loss peak shape studies [12] was Kr, but only at emission angles below 20°, and at these forward angles the strong decrease of the electron loss peak intensity with angle veils any contingent structures in the doubly differential cross section.

Our experiment has been designed to overcome these shortcomings. By using hydrogen projectiles we were able to suppress the smooth background from target ionization in the electron loss peak region to less than 10%, even in a noncoincident experiment. Theoretical estimates for the simultaneous ionization of both projectile and target predict an upper limit of 20% for its contribution to the angular dependent singly differential cross section. This permits us to disregard target ionization in this first interpretation of our data. Krypton was chosen as the target because the Ramsauer-Townsend minima are much narrower than for lighter rare gases and so can be probed with the narrow momentum distribution provided by the H^0 electron. Since only the most rapid variations in energy and angle of the elastic electron scattering cross section are likely to show up in the electron loss peak, it is important to select the collision velocity v such that electrons with energy near $v^2/2$ produce particularly deep minima. For Kr much higher velocities are permitted than for Ar, and this has the advantage that the electron

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loss peak is well separated from the peak of the low energy electrons.

A primary beam of H_2^+ molecules (0.5 MeV/amu) was dissociated in a gas cell and the electrostatically selected H^0 component was collided with a Kr gas jet target. The emitted electrons were analyzed with an electrostatic cylindrical mirror spectrometer [14] which could be rotated under vacuum to accept emission angles θ_f in the range $0° \leq \theta_f \leq 63°$, 90°, and $117° \leq \theta_f \leq 180°$. The energy and angular resolution were $\Delta E/E = 3.14\%$ and $\Delta\theta = 1.67°$. Absolute yields were obtained by means of normalizing to the Rudd, Toburen, and Stolterfoht data [16] as described in the previous work [14]. The uncertainty of the absolute yields is about 80%, while the relative yields are accurate within at most 20%. Figure 1(a) gives a comparison of the singly differential loss cross section, after integrating over the energy interval $0.15 \leq E_f \leq 0.4$ keV, with the differential cross section for equivelocity elastic electron scattering calculated from a model potential including the static and polarization field [17,18]. The lower energy limit for the integration of both theory and experiment was chosen to ensure that any background signal from target electrons was substantially removed (reduced to < 10%) from the data. The experimental data clearly show the second Ramsauer-Townsend minimum near 135°, but it is considerably damped and slightly shifted to larger angles.

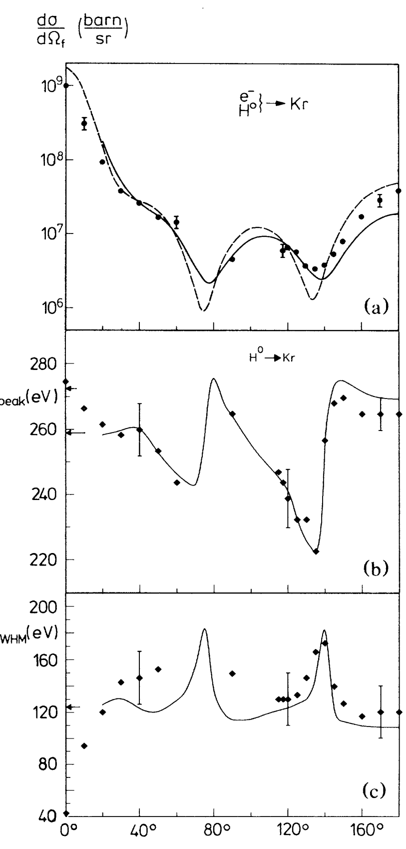

FIG. 1. (a) Angular differential cross section for a krypton target. Theory: (dashed line) elastic electron scattering at energy $v^2/2$, (solid line) EIA for electron loss from H^0 (0.5 MeV). Experiment: ⧱, normalized to EIA at 40°. For absolute cross sections the data points should be multiplied by a factor of 1.27. (b) Position of maximum and (c) full width at half maximum of the electron loss peak for H^0 (0.5 MeV) on krypton. Data here are absolute and shown as ⧱ in (b) and (c). The short and long arrows in (b) denote $v^2/2$ and $v^2/2+\varepsilon_i^P$, respectively. The arrow in (c) denotes the width deduced from the Compton profile.

The presence of the angular variations in the loss cross section prohibits the use of the first-order Born approximation [19,20] which is commonly used to describe electron loss in energetic collisions with light targets such as hydrogen or helium, just as these same variations prohibit the use of this approximation to describe conventional Ramsauer-Townsend oscillations. Instead, a target scattering eigenstate has to be taken for the electron as in the classical electron scattering model [2] or its quantal version, the electron impact approximation (EIA) [17]. However, a recently developed second Born-type theory [21] which accounts for electron propagation in the strong target field has also been quite successful. Our theoretical results are based on the EIA where the doubly differential electron loss cross section is represented as a convolution of the cross section $d\sigma_e/d\Omega(k,\theta)$ for elastic electron scattering with the momentum distribution $\varphi_i^P(\mathbf{q})$ of the bound projectile electron

$$\frac{d^2\sigma^{\mathrm{EIA}}}{dE_f d\Omega_f} = \frac{k_f}{v}\int d\mathbf{q}|\varphi_i^P(\mathbf{q})|^2 \frac{d\sigma_e}{d\Omega}(k,\theta) \times \delta\left(E_f - \varepsilon_i^P - \frac{v^2}{2} - \mathbf{q}\cdot\mathbf{v}\right), \qquad (1)$$

with $k = \max(|\mathbf{q}+\mathbf{v}|, k_f)$ and $\sin\theta/2 = |\mathbf{q}+\mathbf{v}-\mathbf{k}_f|/2k$. Here $E_f = k_f^2/2$ is the energy of the ejected electron and $-\varepsilon_i^P$ its initial binding energy. From Eq. (1) it is obvious that the shape of the electron loss peak is determined by the bound-state momentum distribution if and only if $d\sigma_e/d\Omega$ is a smoothly varying function of the momentum transfer $\mathbf{q}$. Ramsauer-Townsend effects inherent in $d\sigma_e/d\Omega$ are likely to be seen in the *doubly* differential loss cross section if the width of these structures matches the width of the bound electron's momentum distribution. This resonance condition is not required for the *singly* differential cross section $d\sigma^{\mathrm{EIA}}/d\Omega_f$ [which is basically given by the right-hand side of (1) without the δ function]. It is predominantly governed by low momentum transfer ($q \approx 0$) where $K_f \approx v$ such that $d\sigma_e/d\Omega(k,\theta)$ is approximately on shell, and $d\sigma^{\mathrm{EIA}}/d\Omega_f$ is close to the elastic scattering cross section for equivelocity electrons. This is confirmed in Fig. 1(a), where the only difference between EIA and $d\sigma_e/d\Omega(v,\theta_f)$ consists in some damping and shifting of the Ramsauer-Townsend structures.

Figures 1(b) and 1(c) give the energy position E_{peak} of the electron loss peak and its full width at half maximum Γ_{FWHM} as a function of electron angle. Near the location of the Ramsauer-Townsend minima both E_{peak} and Γ_{FWHM} show striking variations which are extremely narrow. For the second minimum, at 140°, the experimental data are well confirmed by the EIA calculations. The strong increase of Γ_{FWHM} at very small angles is related to the transition from the cusp-shaped continuum loss peak to the Compton profile dominated electron loss peak and cannot be reproduced by the EIA which neglects the influence of the projectile on the emitted electron. The region of the Ramsauer-Townsend minimum at 75° is unfortunately not accessible to our spectrometer. Only at those forward and backward angles where $d\sigma_e/d\Omega$ is a smooth function and any cusp contribution has disappeared ($20° < \theta_f < 60°, \theta_f > 160°$) are experiment and theory close to the predictions of the first-order Born theory [20] and the peaked EIA [17]. These predictions are $E_{peak} = v^2/2 + \varepsilon_i^P$ from energy conservation and $\Gamma_{FWHM} = 2vq_H$, where q_H is the half width at half maximum of the projectile's Compoton profile. The high experimental values for Γ_{FWHM} between 30° and 60° are presently unexplained.

In order to elucidate the origin of the peak position and width variations we present in Fig. 2 the doubly differential loss cross sections in the region of the second Ramsauer-Townsend minimum. The increase of the peak width when going from 130° to 140° is clearly evident, as is also its decrease when θ_f is further increased to 150°. From a comparison of the spectral shapes we interpret the very large width at 140° to be an indication of a hidden double-peak structure of the electron loss peak. This can be anticipated from the hump on the low-energy side of the loss peak at 150° which develops into a distinct double-peak structure when the projectile charge is fictitiously increased (in the theory) to $Z_P = 1.5$. Also the sudden change in peak position from $E_{peak} \approx 225$ eV at 130° to ≈ 275 eV at 150° can readily be understood within the double-peak picture: At the smaller θ_f the lower-energy peak is dominant, and at the larger θ_f, the higher-energy peak. This interpretation is supported by calculations at $\theta_f = 150°$ which predict a single peak, at the position of the lower of the two peaks for $Z_P = 1.5$, when the charge is further increased to $Z_P = 2$. From the discussion in connection with Eq. (1) it follows that a variation of Z_P is just as effective in reaching the resonance condition for the visibility of the Ramsauer-Townsend structures in the electron loss spectra as are variations of θ_f or v. In this context attention should be drawn to the recent discovery [22] of Ramsauer-Townsend effects in the region of the binary encounter peak resulting from target ionization by very heavy ions. The splitting of the binary encounter peak into two peaks as a function of emission angle or target charge and the nonmonotonic shift of the peak position with angle which

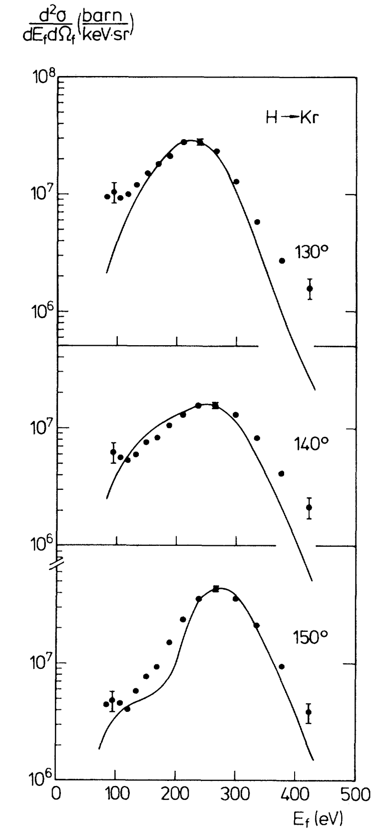

FIG. 2. Doubly differential electron loss cross section for H^0 (0.5 MeV) on Kr at the angles $\theta_f = 130°$, 140°, and 150°. The ordinate values are those predicted by theory. The experimental data (ⵗ) are normalized to the EIA (solid lines) at the peak maximum. To obtain the measured values the data shown should be multiplied by a factor of 1.15 at 130°, 1.83 at 140°, and 1.98 at 150°.

had been clearly seen in the experimental data [22,23] give further support to our conjecture, since the electron loss peak is connected with the binary encounter peak by a mere frame transformation if the collision system is reversed [20].

In conclusion, investigations of the electron loss peak from H^0 (0.5 MeV) on Kr show remarkable variations of the peak position and width with the ejection angle of the electron near those angles where Ramsauer-Townsend minima appear in the elastic electron scattering cross section. We have discovered similar effects when Kr is replaced by the heavier Xe target. We are able to interpret these effects within the electron impact approximation which relates electron loss to quasielastic electron scattering from the target. While for light targets, the peak position and width of the loss peak is mostly determined by the properties of the bound electronic projectile state, there is a strong influence of the target in the case of very heavy atoms. The interference effects of the many partial waves (up to 20 for our system) contributing to electron-target scattering remain visible upon folding with the bound-state momentum distribution, such that the particular shape of the loss peak is governed by the electron distributions of both target and projectile, depending on the choice of collision velocity and ejection angle. This somewhat overdue but successful observation of the Ramsauer-Townsend effect in the electron loss peak gives strong support to the EIA model. A more stringent test of the model would be to use helium projectiles at higher velocity where theory predicts a distinct double-peak structure. However, such an experiment would require a triple coincidence to suppress the background from target ionization.

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