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J. Röder, K. Jung, H. Ehrhardt. Recent progress in low energy atomic hydrogen (e,2e) measurements. Journal de Physique IV Proceedings, 1993, 03 (C6), pp.C6-29-C6-38. 10.1051/jp4:1993603 . jpa-00251688

HAL Id: jpa-00251688

<https://hal.science/jpa-00251688>

Submitted on 1 Jan 1993

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Recent progress in low energy atomic hydrogen (e,2e) measurements

J. RÖDER, K. JUNG and H. EHRHARDT

Fachbereich Physik, Universität Kaiserslautern, 67653 Kaiserslautern, Germany

Abstract:

Coplanar (e,2e) cross sections of atomic hydrogen have been measured 1, 2 and 4 eV above threshold. The angular correlations taken with the constant difference angle $\vartheta_{12}=180^\circ$ show a slight but significant change of the triply differential cross section if the excess energy is lowered from 2 eV to 1 eV suggesting that the extend of the threshold region in atomic hydrogen is smaller than 2 eV. In the angular correlations taken with $\vartheta_1=\vartheta_2$ the two separate peaks found 2 eV above threshold form a single peak if one approaches closer to threshold. The experimental results are compared with the distorted wave Born theory of Jones, Madison and Srivastava (1992) exhibiting deviations with respect to the positions of the peaks and their relative intensities. For fixed angle $\vartheta_1=90^\circ$ the triply differential cross section 2 eV above threshold exhibits a minimum just at $\vartheta_2=90^\circ$. At 1 eV above threshold the minimum has essentially disappeared but the cross section is still not concentrated in an angular region around 90° as could be expected from the Wannier-Peterkop-Rau theory.

Introduction

After the success of modern high energy approximations in the energy region above 100 eV, the electron impact ionisation in the low and intermediate energy range has lately become of greatest interest. Similar as in the high energy case triply differential cross sections of atomic hydrogen will help to perform appropriate approximations for the three-particle Coulomb problem because the wave function in the final state is as simple as possible with no screening of the Coulomb potential by a bound electron. The final state is identical with the double photo ionization of H^- which is also currently under investigation. However, in the electron

impact ionization the initial state is more involved and the final state is less restricted with respect to the quantum states than in the photoionisation. One can hope that the difficulties to describe the fully correlated wave function of two electrons in a Coulomb potential can be overcome rather soon, if reliable experimental data exist.

Apparatus

Fig. 1 shows a side-view of the $(e, 2e)$ -spectrometer used for this investigation. Both detectors can be independently moved around the gas beam in the centre of the vacuum chamber. Detector B can also be moved out of the scattering plane. The rather large electron Faraday cup and the tandem energy selectors in both detectors effectively suppress the background electrons thus allowing to measure outgoing electrons with less than 1 eV. The energy resolution of the spectrometer is normally chosen to be about 350 meV. By continuous improvements of the apparatus the effectivity has been increased in such a way that even with atomic hydrogen 2 eV above threshold up to about 240 true coincidences per minute can be achieved with about the same rate of accidental coincidences. The main improvement was the replacement of the rather narrow glass tube in the microwave resonator by a much wider glass tube without a bottleneck. The new atomic hydrogen source is shown in fig. 2. This modification led to an increase of the dissociation rate and in conjunction with a higher gas pressure in the source to an enlarged density of target atoms in the scattering centre. Finally the change in the atomic source design reduced the measuring time by a factor of about 2.

The replacement of the narrow discharge tube was made possible by changing the cooling system. The original device had been cooled by Frigen streaming up and down in two outer concentric glass tubes. In the new construction the heat is carried away by air which is cooled down by use of the Joule-Thomson effect to about -10° C. The new atomic hydrogen source has the additional advantage that the glass tube has to be replaced less often and can be replaced much faster.

Figure 1. Side - view of the apparatus, showing one electron detector, the electron gun and the atomic hydrogen source.

Figure 2. New design of the atomic hydrogen source. The volume of the microwave discharge region is a factor 4 larger now.

Results and discussion

The low energy region in scattering processes is characterized by the fact that only a few partial waves take part in the collision. Therefore the complexity of the problem is reduced. In 1953 Wannier had concluded from a thorough analysis of the topology of the three particle potential in the far distance zone that the electron impact ionization should exhibit a $E^{1.127}$ dependence where E is the excess energy. Subsequent quantum mechanical studies of Peterkop (1971), Rau (1971, 1976) and Klar and Schlecht (1976) proved that not only the s-wave is involved in the ionization process but also states with higher angular momenta. Even for $l > 0$ the partial waves which are symmetrical with respect to the exchange of r_1 and r_2 , where r denotes the distance to the nucleus, show the $E^{1.127}$ behaviour in agreement with the Wannier law. The waves, however, which are symmetric with respect to the angular and spin coordinates, and therefore in fulfilment of the Pauli principle antisymmetric in r_1 and r_2 , show a $E^{3.881}$ behaviour. For the constant difference angle $\vartheta_{12} = 180^\circ$ Wannier predicted an isotropical behaviour because he assumed only s-wave scattering. Rau allows variations of the cross section with the angle but give only information about the energy dependence. The fact that several partial waves normally take part in the ionizing collision has the consequence that the angular correlations with constant $\vartheta_{12} = 180^\circ$ exhibit characteristic interference pattern for each atom

Figure 3.

Comparison of the triply differential cross section on helium (◆) and krypton (○) for $\vartheta_{12} = 180^\circ$ at an excess energy of 2 eV.

species as can be seen in fig. 3. Especially the s-wave which is able to enter the central part of the potential has strongly different phase shifts for different nuclear charges.

For a given atomic species one can assume that the angular correlations of the triply differential cross sections near threshold do not strongly depend on the primary energy as long as the partial waves obeying the $E^{3.881}$ law can be neglected. Fig 4 compares the cross sections of atomic hydrogen measured in the $\vartheta_{12}=180^\circ$ configuration for 1 eV and 2 eV above threshold. In both cases the cross sections reach their maxima if the detectors are oriented parallel and antiparallel to the primary beam direction. At 90° there are flat minima with very small intensities. The curve taken at 1 eV excess energy, however, is less deep than that at 2 eV. Though the general shape has not changed dramatically, the intensities of the two curves, which are normalized to each other at small scattering angles, differ in the region around 90° by about a factor of two. Pan and Starace (1992) have calculated the cross section for 0.5 eV excess energy for $\vartheta_{12}=180^\circ$ finding a flat local maximum at 90° , which could be consistent with our results.

For the angular correlations with varying difference angle the situation is more complex. Here the main aspect of the Wannier analysis should be still valid namely that just at threshold the mutual screening effects of the outgoing electrons force the elec-

Figure 4.

Comparison of the triply differential cross section on atomic hydrogen for $\vartheta_{12} = 180^\circ$ at excess energies of 2 eV (+) and 1 eV ($\diamond$).

trons to follow trajectories which asymptotically enclose an angle of π at zero excess energy. Both electrons can only escape if they are on opposite sides of the ion.

For the geometry with fixed $\vartheta_a = 90^\circ$ at 2 eV above threshold (Brauner et al 1990) and in the so called coplanar symmetric geometry with $E_1 = E_2$ and $\vartheta_1 = \vartheta_2$ at the same incident energy (this work) the results seemed to contradict the requirements of the Wannier theory. In both measurements a minimum instead of a maximum is found opposite to the direction of the detector A. Therefore we decided to measure at lower excess energies, i.e. closer to threshold in order to check whether this behaviour changes or not.

One series of measurements concerns the coplanar symmetric geometry. From symmetry considerations it can be concluded that only singlet states can contribute to these collisions. At large energies there is one peak around about 45° corresponding to the binary collision geometry and a second peak at 135° with orders of magnitude less intensity. The second peak is theoretically reproduced by the second Born amplitude. That means a double collision is necessary to bring the electrons into this configuration. Reducing the impact energy leads to a shift of the peaks towards 90° because the electron-electron interaction prevents the electrons to escape close to each other. In addition the intensity ratio changes dramatically, until at low energies the second peak is more prominent than the first. In the case of helium 2 eV above threshold both peaks have come together at 90° in agreement with the Wannier result.

Fig. 5 shows a series of hydrogen results ranging from 25 eV to

Figure 5. Coplanar symmetric triply differential cross sections on atomic hydrogen at various incident energies given in the diagrams. —, distorted wave Born approximation of Jones and Madison (1993); $\blacklozenge$, this work

14.6 eV taken in this coplanar symmetric geometry. At 25 eV impact energy the typical high energy behaviour can be observed. The distorted wave Born approximation of Jones and Madison predicts an intensity ratio of the two maxima of about 27 instead of 3 found in the experiment. The two peaks calculated in the theory also appear at different angles. At 20 eV the second peak is already more intense than the first one in the measured cross section, but this is not found in the theory. Even at 15.6 eV both peaks are clearly separated, but the positions have already been changed. Here the best agreement between theory and experiment is observed. At 14.6 eV, however, there is only one broad peak still revealing his double peak origin similar to the 30 eV result in the case of helium. If one would approach even closer to threshold a single peak at 90° can be expected. The differences between theory and experiment seem to be mainly caused by the difficulties to describe the electron-electron repulsion more accurately.

The traditional angular correlations taken with one detector at a fixed position also allow tests of the Wannier theory. Fig 6 shows a series of measurement on atomic hydrogen for $\vartheta_a=90^\circ$ with decreasing excess energy. In contrast to all corresponding results in helium and to the angular correlations of atomic hydrogen taken at small and large scattering angles which exhibit a peak just opposite to the position of the fixed detector the cross section shows a split distribution with a sharp minimum at 90° for the two measurements taken at 17.6 eV and 15.6 eV. At 1.4 eV above threshold the minimum disappears. However, even at 1 eV excess energy the angular correlation shows a broad asymmetric distribution, probably caused by interfering symmetric and antisymmetric partial waves.

All measurements presented indicate that the typical threshold behaviour in the case of atomic hydrogen is only found in an excess energy range of less than 2 eV or even less than 1 eV. For all atomic systems studied until now the validity range of the threshold law seems to be the least one for atomic hydrogen. For example in the case of helium the threshold behaviour can be observed up to an excess energy of about 3-4 eV. In the case of the innershell ionisation of neon Hink et al (1981) even found the $E^{1.127}$ dependence still about 90 eV above threshold. In the case of atomic hydrogen also the systematic shifts of the peaks in the coplanar symmetric configuration seems to be smaller than for example in the case of helium for similar excess energies. There-

Figure 6. Triply differential cross sections on atomic hydrogen for fixed angle $\vartheta_a = 90^\circ$ and various incident energies in arbitrary units.

fore one could erroneously assume the electron-electron repulsion being less important in the case of atomic hydrogen than in the case of atoms with larger nuclear charge. In fact, the angular correlation at threshold seems to be mainly determined by interference effects of processes going on in the initial and in the final state. C. T. Whelan (1993), who took into account in a crude approximation polarization and post collision interaction effects, could reproduce quite well coplanar symmetric results of helium and atomic hydrogen at low energies.

The rather fast change of the cross sections above threshold, which has been demonstrated in fig. 5 and fig. 6, makes it nec-

essary to determine the triply differential cross section for several closely spaced primary energies just to reveal all details of the transition from the pure threshold situation characterized by the dominant mutual screening effect to the situation at about 4 eV excess energy where other mechanisms prevail.

Acknowledgements

We thank Professor D. Madison and Dr. S. Jones for providing the theoretical data prior to publication. The financial support of the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

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